Technical Memorandum

SEISMIC HAZARD STUDY
DEVIL'S SLIDE TUNNELS

Prepared for
Caltrans

and
HNTB Corporation

August 2001

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DEVIL'S SLIDE TUNNELS PROJECT

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Table of Contents

Tables

Figures

Appendices

1.0 Introduction

This report presents results of two subtasks conducted by Earth Mechanics, Inc. with collaboration from Dr. Norm Abrahamson for establishing the initial benchmark of seismic ground motion criteria for the Devil's Slide Tunnels. The first subtask involved conducting both deterministic and probabilistic seismic hazard analyses to develop the target design rock spectra at the site. Then, in the second subtask, spectrum-compatible rock motion time histories were generated; those time histories matched the shaking level of the target design rock spectra developed from the seismic hazard analyses in the first sub task.

The reference rock spectra and the spectrum-compatible rock motions developed in these two subtasks are intended to be used in further seismic design analyses where the seismic ground motion criteria are to be further defined, including site response and scattering analyses to take into account the local site conditions and topographic features. Wave scattering from site-specific topographic features (especially reflecting site specific rock joint orientations) are important for consideration of rock slope stability issues adjacent to the tunnel portal structures. Scattering analyses (including the excavated tunnel configuration) are also necessary to evaluate the degree of ground distortion (in addition to the overall dynamic ground shaking as depicted by the response spectra and the spectrum-compatible time histories documented in this report). Results from these additional seismic design tasks from using the generated rock motion spectra and time histories are to be reported in the future.

2.0 Seismic Sources

Figure 1 presents a fault map of the Northern California region with the Devil's Slide tunnels site shown on the map. This is the fault map adopted by Caltrans for design of typical highway bridges (Mualchin, 1996) which adopts the deterministic maximum credible earthquake approach. The San Andreas fault to the east and the San Gregorio fault to the west are the dominant seismic sources for the Devil's slide tunnels site. Due to their high activity rates and close proximities, the two faults contribute virtually all the seismic hazard for the project at the long return periods of design interest. All the faults shown in the map have been considered in the seismic hazard analysis even though they contribute very little to the seismic hazard. Random areal sources have also been included in the analyses that would take into account potential smaller unknown faults at the project site. Table 1 presents the input parameters of the major faults used for the probabilistic seismic hazard analysis. The magnitude defined in Table 1 corresponds to the mean characteristic earthquake magnitude used for deterministic seismic hazard analysis. A magnitude of 7.25 was used for the San Gregorio fault. In probabilistic hazard analysis, the maximum magnitude is 7.5, consistent with the Caltrans hazard map procedure for MCE.

As shown in Figure 1, the San Gregorio fault is located at about 3 kilometers from the western limit of the Devil's Slide tunnels site, while the San Andreas fault is located at about 8 kilometers from the eastern limit of the site. As to be discussed later, the closer San Gregorio fault (capable of a magnitude 7.5 earthquake) would cause stronger ground shaking at the site than the San Andreas fault (capable of a magnitude 8.0 earthquake) and was found to be the controlling fault for design. The overall strike angle of the San Gregorio fault is oriented at about N22^{o}W, while the longitudinal axis of the Devil's slide tunnels is oriented at about the N23^{o}E direction. Therefore, the longitudinal (tunnel axis) as well as the transverse directions of the tunnel would be oriented at about a 45^{o} from both the fault normal and the fault parallel directions; implying that the shaking intensity would be about equal for the longitudinal and transverse directions.

3.0 Target Reference Rock Spectra

A meeting was held on May 29 at HNTB's Oakland office among the project team, Caltrans personnel and the Devil's slide tunnels Advisory Panels to discuss the approach for establishing the seismic ground motion criteria for the project. It was agreed that for consistency with Caltrans practice for ordinary non-lifeline structures, a deterministic approach should be used for developing the ground motion criteria. Probabilistic seismic hazard analyses should also be conducted for cross comparison, to guide the degree of adjustments for near-fault rupture directivity effects.

Following the May 29 meeting, the project team conducted both probabilistic as well as deterministic seismic hazard analyses. Results from the analyses were presented to the Advisory Panels and Caltrans personnel during a June 20 meeting. During the meeting, Dr. Norm Abrahamson distributed and presented results of his ground motion hazard analyses for the Devil's Slide tunnels site to Caltrans, the Advisory Panels and the HNTB Project Team.

The materials distributed during the June 20 meeting have been attached as Appendix A in this report. The appendix includes uniform-risk equal hazard spectra for two horizontal (fault normal and fault parallel) component motions from probabilistic analyses at seven return periods (72, 100, 200, 500, 1000, 1500 and 2500 year). They were compared with results of deterministic analyses (maximum credible earthquake, or MCE) from each of the San Gregorio and the San Andreas faults using median, 69th percentile (i.e. mean-plus-half-sigma) and 84th percentile (i.e. mean-plus-sigma) attenuation relationships. The seismic hazard analyses were conducted by averaging (i.e. applying equal weighting factors on) the three commonly used models: (1) the Sadigh's (Geomatrix, 1995), (2) the Idriss (1991) and (3) the Abrahamson and Silva (1997) rock attenuation relationships.

The three horizontal rock motion attenuation relations were adjusted to account for near-fault directivity effects using a modified form of the Somerville et al. (1997) fault-rupture directivity model. Somerville et al (1997) developed an empirically based model quantifying the effects of rupture directivity on horizontal response spectra that can be used to scale the average horizontal component computed from attenuation relations. The Somerville et al. (1997) model comprises two period-dependent scaling factors that may be applied to any ground motion attenuation relationship. One of the factors accounts for the increase in shaking intensity in the average horizontal component of motion due to near-fault rupture directivity effects. The second factor reflects the directional nature of the shaking intensity using two ratios: fault normal (FN) and fault parallel (FP) versus the average (FA) component ratios. The fault normal component is taken as the major principal axis resulting in an FN/FA ratio larger than 1 and the fault parallel component is taken as the minor principal axis with an FP/FA ratio smaller than 1. The two scaling factors depend on whether fault rupture is in the forward or backward direction, and also the length of fault rupturing toward the site.

During the San Francisco-Oakland Bay Bridge (SFOBB) east span replacement design project, the Sommerville et al (1997) near-fault directivity model was reviewed by Dr. Norm Abrahamson, the Seismic Peer Review Panel and Earth Mechanics Personnel (the project geotechnical engineer). Special studies were conducted by three groups of world renown seismologists. The study led to some modifications of the Sommerville model as documented in the SFOBB ground motion report

(Fugro-Earth Mechanics, 2001). The SFOBB near-fault directivity model is referred as the modified Sommerville model and adopted for the Devil's slide tunnels project. In summary, the SFOBB near-fault directivity model improved on the Sommerville (1997) model by taking better account of saturation in ground shaking for very large magnitude earthquakes and reduces the degree of increase in long period shaking attributed to the near-fault directivity effects, especially for large earthquakes.

The materials distributed during the June 20 meeting, also included materials delineating the near-fault-rupture directivity effects (which will increase ground shakings at periods longer than 1 second range) based on the work developed for the SFOBB project as discussed above (Fugro-Earth Mechanics, 2001). The probabilistic hazard solutions (which included randomized fault rupturing scenarios) were compared to three deterministic (MCE) solutions: (1) standard attenuations (i.e. w/o directivity adjustments), (2) adjusted for the most severe directivity scenario, and (3) adjusted for a moderate directivity scenario (cube root of the most severe directivity adjustment). Within the period of interest for the Devil's slide tunnels project (say up to 2 second period), the deterministic earthquake from the San Gregorio fault will have higher shaking than the more distant but larger magnitude earthquake from the San Andreas fault. Therefore, the San Gregorio fault can be regarded as the controlling fault for the Devil's slide tunnels project so far as shaking amplitude is concerned.

It was agreed, during the June 20 meeting that ground motion criteria for the Devil's slide tunnels project should be consistent with standard Caltrans practice and be based on a deterministic approach using median attenuation relationships. Because the site is very close to major faults, it was agreed that standard attenuation relationships need to be adjusted at long periods to account for recent advances in near fault rupture directivity effects. The equal hazard spectra for the 500-year return period event from probabilistic hazard analyses were used to guide the degree of adjustment for the MCE earthquake to account for the near fault directivity adjustment. The following lists the bases for determining the reference rock motion spectra for the Devil's slide tunnels project with consensus among all parties including Caltrans, the Advisory Panels and the HNTB team members:

- Deterministic MCE approach, using the appropriate median attenuation relationship, will be used to establish the ground motion criteria for the Devil's Slide Tunnels project.

- The 500-year return period probabilistic earthquake will be used to guide the degree of adjustment to account for the near fault directivity effects.

- Based on results of the 500-year return period probabilistic earthquake, the target spectra based on median attenuation relationship was adjusted for a moderate level of near fault directivity effects.

- The San Gregorio fault is the controlling fault for the ground shaking amplitude.

The vertical motion reference spectrum is based on applying period-dependent ratios of vertical to the horizontal fault parallel spectrum based on conventional attenuation relationships for the appropriate scenario earthquake. A minimum threshold of vertical to horizontal ratio of 2/3 was also to be implemented for developing the vertical ground motion spectrum.

Figure 2 presents the resultant target rock spectra adopted for the design of the Devil's slide tunnels project. The figure presents the 5% damped spectra in terms of both acceleration and relative displacement spectra. Table 2 presents the coordinates of the three component target rock spectra. In addition to the target rock spectra in the fault normal and fault parallel directions, the target spectra in the intermediate 45-degree direction have also been presented in Figure 2 and Table 2 because the longitudinal and transverse directions of the tunnel are oriented at about 45 degrees from the fault directions. Additional discussions on the methodology to transform the fault normal/fault parallel spectra to the 45-degree angle will be provided in Section 6.

As shown in Table 2, the peak ground acceleration (PGA) for the design earthquake is estimated at 0.66g based on the arithmetic mean of the median value predicted from the three adopted attenuation relationships. As discussed earlier, combination of a mean characteristics Magnitude of 7.25 at 3 kilometers was used for the San Gregorio fault. The resultant PGA of 0.66g compares favorably with the 0.63g PGA solution from the Caltrans Seismic Hazard Map (Lalliana Mualchin, 1996), even though the Caltrans map assumes a Magnitude 7.5 earthquake for the San Gregorio fault. The Mualchin's procedure also confirms that the San Gregorio fault would lead to higher shaking than the larger magnitude, but more distant San Andreas event.

4.0 Spectrum-Compatible Time Histories

During the June 20 meeting, it was also decided to develop three sets of rock motion histories that would be spectrum-compatible to the reference design spectra (presented in Figure 2). Results of deaggregated hazards from the probabilistic analyses have also been included in Appendix A. The results indicate that at return periods at 500-year and longer, forward rupturing scenarios events from the San Gregorio or the San Andreas faults with large magnitude earthquakes (i.e. magnitude above 7.5) will dominate the hazards. Theoretically, the choice of design earthquake time histories should be based on the deaggregation solutions.

To be compatible with the deaggregated hazards, two of the motion sets will represent forward rupturing events. However, because strong motion records from forward rupturing events tend to have shorter durations, the third set of motion will be selected from longer duration backward rupturing events in order to provide a comprehensive set of ground motion characteristics for design applications. The following start-up motion sets (proposed by Dr. Abrahamson) were adopted:

(1) The Yermo Fire Station Record from the 1994 Magnitude 7.4 Landers earthquake. This would represent a forward rupturing events.

(2) Another forward rupturing event will be selected from the Arcelik record from the 1999 Magnitude 7.4 Kocaeli, Turkey earthquake.

(3) The backward rupturing (i.e. longer duration) earthquake record will be selected from the Joshua Tree Station Record from the 1994 Magnitude 7.4 Landers earthquake.

Detailed information of the discussed startup motion records has been included in Table 3, including the magnitude of the earthquake event, distance of the recording station and the soil condition at the site and the major principal and minor principal directions assigned to the fault normal and fault parallel motions, respectively. Plots of the time histories and their corresponding response spectra of the original startup motions are presented in Appendix B.

5.0 Procedure for Developing Spectrum-Compatible Time Histories

The procedure for generating the spectrum-compatible rock motion histories involves three basic steps:

Step-1 would be to rotate the pair of horizontal component motions for each startup record to their principal axes, such that the resultant orthogonal horizontal component motions would have a minimal (absolute value) cross-correlation coefficient. For the Devil's slide tunnels project, the earlier listed three sets of startup motions were rotated to their principal axes as defined by a zero cross correlation coefficient computed using the time history records. Further discussions on this subject will be presented in the forgoing sections.

Step-2 involves modifying each of the two horizontal component motions (after rotation to their principal axes) such that the major principal component motion would match the stronger shaking fault normal target spectrum and the minor principal component motion would match the weaker fault parallel target spectrum presented in Figure 2 (tabulated in Table 2).

Design rock motions are then developed by modifying their acceleration time histories so that their spectra are similar to the intended design spectra. The selected initial time histories (usually empirical recordings) are gradually modified through an iterative process so that the response spectrum of the modified time history is compatible with the target spectrum. Various methods have been developed to perform the spectrum matching. A commonly used method adjusts the Fourier amplitude spectrum based on the ratio of the target response spectrum to the time history response spectrum while keeping the Fourier phase of the reference history fixed. An alternative approach for spectral matching adjusts the time history in the time domain by adding wavelets to the reference time history. In this study, the time domain method is used. The time histories were first scaled to the target peak acceleration and then the time histories were modified by adding small wavelets to the time history so that the resulting time history has a spectrum that is close to the target. This time domain approach preserves the gross non-stationary properties of the recorded ground motion. It usually minimizes the necessary modifications and better preserves the features of the startup motions.

Step-3 involves correcting the baseline of the resultant spectrum-compatible histories.

As discussed above, because of the close distance to the San Gregorio fault, the earthquake ground motion for the Maximum Credible earthquake event is projected to exhibit strong near fault rupture directivity features. The motion at long period range has a strong directional feature and the fault normal directional shaking is significantly stronger than the fault parallel directional shaking. During generation of the spectrum-compatible motion, it was discovered that when spectrum matching is conducted in the fault normal and fault parallel directions, the resultant motion, when rotated to the tunnel axes (i.e. in the longitudinal and transverse tunnel, or the 45-degree angle directions) has shaking that deviated from its intended shaking level (i.e. the 45-degree target spectrum shown in Figure 2). It was discovered that the ground motion that is spectrum-compatible in the principal fault axes will inherently have shaking that is overly conservative in the direction at 45-degree from the fault axes. On the other hand, if spectrum matching is conducted in the principal tunnel axis directions (i.e. the tunnel longitudinal and transverse directions), the resultant shaking becomes too low when they are rotated to the fault normal direction. At the present time, there is no satisfactory method to develop a set of ground motion which would be spectrum-compatible in all rotated directions simultaneously, without destroying the basic appearance of the near-fault displacement time history in the startup motion.

Due to the discussed difficulty, it was decided during an Advisory Board Meeting dated July 31, to provide two redundant sets of input rock motions as follows:

Set-1A, Set-2A and Set-3A motion sets (from the three sets of selected startup motions) are to be developed from spectrum matching conducted in the fault normal / fault parallel axes. These are the original three sets of motions presented to the Advisory Board prior to the July 31 meeting in an earlier draft of the ground motion report. The startup motions are first rotated to their major and minor principal axes based on zero cross correlation coefficient from the displacement histories. The Set-1A three-component rock motions are presented in Figures 3 thru 5, in the fault normal and fault parallel directions. Each of the figures presents the acceleration, velocity and displacement histories with their corresponding response spectra (both acceleration and displacement spectra) shown in the lower part of the figure. The target spectra have also been shown in the spectral plots (as dotted lines) for cross comparison. In addition to presenting the rock motions in their principal fault axes, Figures 6 and 7 present the Set-1A horizontal rock motions as rotated to the 45-degree and 135-degree counter clockwise from the fault normal direction. The lower part of each figure presents the spectra from the time history record as compared with the 45-degree target spectra. Figures 8 through 12 present the corresponding Set-2A rock motion and Figures 13 through 17 present the corresponding Set-3A rock motions. Table 4 summarizes the peak acceleration, velocity and displacement values of the three sets of spectrum-compatible time histories from spectrum matching conducted in the fault normal and fault parallel directions. They can be compared to the startup motions tabulated in Table 3.

Set-1B, Set-2B and Set-3B motion sets are the alternate rock motion sets developed from spectrum matching conducted in the longitudinal and transverse tunnel axes (i.e. at 45-degee rotation from the fault axis). These motion sets were generated based on discussions with the Advisory Board during the July 31 meeting. The startup motions are first rotated to their major and minor principal axes based on zero cross correlation coefficient from the velocity histories. The Set-1B three-component rock motions are presented in Figures 18 and 19, in terms of the tunnel axes coordinate system (i.e. at 45-degree angle from the fault axes). Figures 20 and 21 present the Set-1B horizontal rock motions in the fault normal and fault parallel axis directions. Figures 22 through 25 present the corresponding Set-2B rock motions and Figures 26 through 29 present the corresponding Set-3B rock motions. The vertical component motion is unaffected by whether spectrum matching is conducted in the fault or the tunnel axes and the vertical motions (i.e. those shown in Figures 5, 10 and 15) in the earlier Set-A motions can be used for the Set-B motions. Table 5 summarizes the peak acceleration, velocity and displacement values of the three sets of spectrum-compatible time histories, from spectrum matching conducted in the 45-degree directions.

It can be observed that, in general the motion sets that are matched to the fault normal / fault parallel target spectra tend to have higher shaking than the motion sets matched to the tunnel axis target spectrum. For period range below 2 second, the difference between the two alternate motion sets is not too drastic and acceptable. However, at longer period range (say at 5 seconds), the difference becomes more significant. Therefore, either the Set-A or the Set-B motion sets should give about the same level of response and either motion sets would be adequate for designing for short-period structures. The Set-A motion is preferred for application because it is more defendable on the basis of conservatism.

6.0 Horizontal Shaking Under Rotation and Cross Correlation Coefficients

In addition to checking for spectrum-compatibility at the fault normal and fault parallel directions shown the discussed figures, we have also plotted the ground motion shaking intensity and their cross correlation coefficients in rotated directions in Figures 30 through 32 for the Set-1A, Set-2A and Set-3A motions, respectively. The shaking intensity and cross correlation coefficients under rotation are plotted for the Set-1B, Set-2B, and Set-3B motion sets in Figures 33 through 35, respectively.

The upper part of the figures show the shaking intensity in rotated directions from the benchmark fault normal / fault parallel directions by first rotating the pair of fault normal / fault parallel motions to other directions in 10-degree increments and then computing the response spectrum of the rotated motions. The resulting spectral amplitude of the rotated motion is plotted against the corresponding orientation in a polar coordinate plot. The angle in the polar coordinate plot denotes the angle of rotation, and the radial distance from the origin denotes the spectral amplitude after they are normalized by the response in the fault normal direction. The spectral displacement from the fault normal target spectrum (as tabulated in Table 2) has been used for normalization in the polar shaking intensity plots. The normalizing spectral displacement has also been tabulated under each of the six shaking intensity plots. The polar shaking intensity plots are presented for 6 periods at 1, 1.5, 2, 3, 4 and 5 second. The ellipses shown on each of the shaking intensity pattern can be regarded as the target shaking intensity pattern as extrapolated from the target rock spectra from the fault normal and fault parallel directions as tabulated in Table 2. Such (period dependent) elliptical shaking intensity patterns can be used to deduce the target spectra in directions rotated from the fault normal / fault parallel directions. The target spectrum at the 45-degree angle shown in Table 2 and plotted in Figure 2 was developed from such elliptical shaking intensity patterns.

Below each of the shaking intensity plots are the cross correlation coefficients computed based on the horizontal component acceleration, velocity and displacement histories. The cross-correlation coefficient is defined in the following page.

The variance for motion in x- and y-directions are defined as s^2_x and s^2_y in the following equations.

$$s_x^2 = \frac{1}{t_d} \int \left[a_x(t) - a_{x\,mean} \right]^2 dt \qquad s_y^2 = \frac{1}{t_d} \int \left[a_y(t) - a_{y\,mean} \right]^2 dt$$

where a_x(t) and a_y(t) are the two orthogonal horizontal component acceleration histories with the respective arithmetic means denoted by the values of $a_{x\,mean}$ and $a_{y\,mean}$.

he covariance μ_{xy} is defined in the following equation.

$$m_{xy} = \frac{1}{t_d} \int \left[a_x(t) - a_{x\,mean}\right]\left[a_y(t) - a_{y\,mean}\right] dt$$

Then, the cross-correlation coefficient of motions a_x (t) and a_y (t) is defined as

$$\mathbf{r}_{xy} = \mathbf{m}_{xy}/(\mathbf{s}_x \mathbf{s}_y) \qquad -1 \le \mathbf{r}_{xy} \le 1$$

The lower portions of Figures 30 thru 35 present the discussed cross-correction coefficients computed using the acceleration, velocity and displacement time histories. In addition to solutions at the original reference axes (i.e. fault normal/fault parallel directions), the cross-correlation coefficient computations of rotated motions have also been conducted by rotating the motions through 360-degrees about the vertical axis at 10-degree increments; similar to the shaking intensity plot shown in the upper portion of the figure. Again, the computed cross-correlation coefficient amplitudes were plotted against their corresponding angular rotation in polar coordinate plots. However, in order to depict both positive and negative cross-correlation values, the coefficient amplitudes are measured from a reference circle shown in the figure as dotted lines rather than from the origin. The region outside the dotted circle (radial distance larger than the reference circle) denotes positive cross-correlation coefficient values, whereas the region inside the reference circle denotes negative coefficient values.

As discussed earlier, the tunnel axis is oriented at about 45-degree in between the fault axes. Therefore, ground shaking in the 45-degree angle from the fault axes would be of design interest. The target spectrum in the 45-degree angle has also been presented in Table 2 and Figure 2 along with the target spectra in the principal fault axes. As discussed earlier, because of difficulty to achieve spectrum-compatibility in all rotated directions, especially at very long period range (say up to 5 second), we have generated two alternate sets of rock motions (i.e. Sets-A and Set-B) to allow more option in design analyses. Whereas, further iterations might be able to improve the feature of spectrum-compatibility in rotated directions (i.e. matching principal fault axes and at the 45-degree axis, simultaneously), the operation tends to destroy the near-fault directivity features, especially in the resultant displacement histories. Therefore, over manipulation of the time history records could be counter productive.

7.0 Lifeline Issues

During several meetings, some discussions have been raised regarding the need to conduct sensitivity studies to appreciate the cost impact to design the Devils Slide Tunnels to a higher standard compatible to the performance goal expected for lifeline structures. There was a consensus (among the Advisory Panels, Caltrans and the Project Design Team) that it would be adequate to conduct these additional studies making use of the standard design motion sets (i.e. the benchmark MCE design motions). Then, adjustment factors (based on shaking amplitude of longer return period motions, say a 1,000-year return period event, to the MCE benchmark motion) can be applied to the basic design motions for the sensitivity study. Whereas the adjustment factors would be period dependent, the appropriate scaling factor can be chosen based on the dominant period of design interest. For simplicity, ratios between the 1,000-year return period and the500-year return period can be used as the period dependent adjustment factors. Some discrete adjustment factors are 1.23, 1.26 and 1.35 at periods 0.01, 0.2 and 2 seconds, respectively.

8.0 Summary and Conclusions

The presented ground motion criteria and the three sets of rock motions have been furnished to document the spectrum-compatible rock histories generated for the Devil's slide tunnels project. We have two appendices in this report to provide other background information. Appendix A presents further details of the conducted probabilistic and deterministic seismic hazard analyses as discussed earlier. Appendix B presents additional details of the original startup motions used for development of the spectrum-compatible motions. This appendix included time history plots of the startup motion after rotating to their principal axes. Comparisons between the startup motions to the resultant spectrum-compatible motions have also been included. Plots of shaking intensity under rotation and cross correlations of the startup motions have also been included in Appendix B.

The reference target rock spectra and their corresponding spectrum-compatible time histories represent the first benchmark rock ground motion criteria. One of the implicit assumptions of the developed motions is a level ground topographic feature. The reference spectra and the developed rock motions are intended to be used in further site scattering analyses. Such analyses are needed to account for more localized geologic features, including site-specific topographic and soil properties collected from the Devil's slide tunnels project. Wave scattering from site-specific topographic features (especially reflecting site specific rock joint orientations) could be important for consideration of rock slope stability issues adjacent to the tunnel portal structures. Scattering analyses (including the excavated tunnel configuration) are also necessary to evaluate the degree of ground distortion (in addition to the overall dynamic ground shaking as deduced from conventional response spectral plots). The discussed future analyses using the generated rock motion histories would be important for establishing the ground motion criteria for portal stability and tunnel liner response evaluations.

The following presents a summary of the major conclusions and recommendations developed from the Advisory Panel, Caltrans and the HNTB Project Team during the three project meetings (dated May 29, June 20, 2001 and July 31, 2001):

- Deterministic MCE approach from the San Gregorio Fault capable of a Magnitude 7.5 earthquake at 3-kilometer distance would be the controlling fault for ground shaking amplitude aspects.

- Ground shaking in terms of the three component ground motion design response spectra should be based on the appropriate median confidence level attenuation relationships, but be adjusted for a moderate level of near fault directivity effects.

- The adopted deterministic MCE earthquake corresponds to roughly a 500-year return period probabilistic earthquake.

- From the probabilistic hazard analyses, the most likely earthquake event would be a forward rupturing event on the San Gregorio fault. Two out of the three motion sets were developed from forward rupturing earthquake records. The third motion set was selected from a backward rupturing earthquake record for a longer duration of ground shaking.

- Two alternate sets of rock motions (i.e. Sets A and Sets B) are provided. The Set-A motions are generated from spectrum matching conducted in the principal fault axes and the resultant shaking at very long periods tend to overshoot the target spectrum in the principal tunnel axes (i.e. in the longitudinal and transverse tunnel directions). However, this Set-A motions should be reasonable for shorter periods (i.e. less than 2 second period) and can be regarded as the primary motion sets for design analysis. To provide for more options in design analyses, an alternate sets of rock motions (i.e. Sets B motion sets) are generated from spectrum matching conducted in the tunnel axes. This motion set has better spectrum-compatibility features in the principal axes of the tunnel, but can be deficient in long period motion in the fault normal direction.

- For the north portal, south portal, and south rock cut, it was agreed to design these structures using "lifeline" criteria due to their vulnerability. The tunnel itself will still be designed for non-lifeline criteria due to lower vulnerability. The "lifeline" ground motion can be obtained by scaling the MCE motion by a scaling factor. A ratio of 1.35, deduced based on the 1,000-year versus the 500-year spectra at 2-second period, is used as the scaling factor for slope stability evaluation where peak velocity rather than peak acceleration governs.

9.0 References

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Sommerville, P.G., Smith, N.F., Graves, R.W. and Abrahamson, N.A. 1997. Modification of Empirical Strong Motion Attenuation Relations to Include the Amplitude and Duration Effects of Rupture Directivity, Seismological Research Letters, Volume 68, No. 1, January / FebruaryTable 1. Seismic Sources and Source Parameters used in the Seismic Hazard Analysis.

TABLE NO. 1

Seismic Sources and Source Parameters Used in the Seismic Hazard Analysis

Fault	Recurrence Interval (yrs)	Slip Rate (mm/yr)	Fault Width (km)	Mean Characteristic Magnitude
Hayward		7.0 (0.25) 9.0 (0.50) 11.0 (0.25)	12.0 (0.5) 15.0 (0.5)	7.05 (0.5) 7.35 (0.5)
Marsh Creek/Greenville Arroyo		0.5 (0.25) 2.0 (0.50) 3.0 (0.25)	12.0 (1.0)	6.9 (1.0)
Rodgers Creek		6.0 (0.25) 8.0 (0.50) 11.0 (0.25)	12.0 (1.0)	7.25 (1.0)
San Andreas – North Coast	170 (0.25) 210 (0.50) 260 (0.25)	17.9* (0.25) 22.4* (0.50) 28.0* (0.25)	12.0 (1.0)	7.90 (1.0)
San Andreas – Santa Cruz	320 (0.25) 400 (0.50) 500 (0.25)	4.2* (0.25) 5.3* (0.50) 6.6* (0.25)	18.0 (1.0)	7.00 (1.0)
San Andreas – Peninsula	320 (0.25) 400 (0.50) 500 (0.25)	3.2* (0.25) 4.1* (0.50) 5.1* (0.25)	14.0 (1.0)	7.10 (1.0)
Calaveras – Northern Segment		2.0 (0.25) 6.0 (0.50) 8.0 (0.25)	12.0 (1.0)	6.9 (1.0)
Calaveras – Southern Segment		13.0 (0.25) 15.0 (0.50) 17.0 (0.25)	12.0 (1.0)	7.0 (1.0)
Green Valley/Cedar Roughs		1.5 (0.20) 4.0 (0.60) 5.0 (0.20)	12.0 (1.0)	6.85 (1.0)
San Gregorio		1.0 (0.25) 2.0 (0.50) 3.0 (0.25)	15.0 (1.0)	7.25 (1.0)

Notes:

1. Ranges of values assumed for each parameter are shown with weights in parenthesis.
2. All faults are vertical strike-slip faults with Richter b-value = 0.90
3. Rupture Area Relation: $\mathrm{Log}_{10}(A) = -3.49 + 0.91\,M$ $\mathrm{Sigma}(\mathrm{Log}_{10}) = 0.24$
   Rupture Width Relation: $\mathrm{Log}_{10}(W) = -1.01 + 0.32\,M$ $\mathrm{Sigma}(\mathrm{Log}_{10}) = 0.15$
4. Characteristic recurrence model weighted 0.9; exponential recurrence model weighted 0.1.

* Slip-rate computed from the recurrence interval.

5. The minimum magnitude used in the hazard calculation is 5.0. Smaller magnitude events do not contribute significantly to ground motions of engineering interest.

TABLE NO. 2
Coordinates of Reference Rock Motion Target Spectra

	Spectral Acceleration, PSA (g)			Relative Displacement, Rd (cm)			Target at 45-Deg	
Period (sec)	**Fault Normal**	**Fault Parallel**	**Vertical**	**Fault Normal**	**Fault Parallel**	**Vertical**	**PSA (g)**	**Rd (cm)**
0.010	0.666	0.666	0.636	0.002	0.002	0.002	0.666	0.002
0.020	0.666	0.666	0.636	0.007	0.007	0.006	0.666	0.007
0.030	0.683	0.683	0.755	0.015	0.015	0.017	0.683	0.015
0.075	1.070	1.070	1.379	0.150	0.150	0.193	1.070	0.150
0.100	1.230	1.230	1.388	0.306	0.306	0.345	1.230	0.306
0.150	1.550	1.550	1.312	0.867	0.867	0.734	1.550	0.867
0.160	1.600	1.600	1.294	1.018	1.018	0.823	1.600	1.018
0.180	1.636	1.636	1.247	1.318	1.318	1.004	1.636	1.318
0.200	1.650	1.650	1.197	1.641	1.641	1.190	1.650	1.641
0.230	1.647	1.647	1.151	2.165	2.165	1.514	1.647	2.165
0.260	1.622	1.622	1.099	2.725	2.725	1.846	1.622	2.725
0.280	1.600	1.600	1.067	3.118	3.118	2.079	1.600	3.118
0.300	1.560	1.560	1.040	3.491	3.491	2.327	1.560	3.491
0.400	1.378	1.378	0.919	5.482	5.482	3.655	1.378	5.482
0.500	1.170	1.170	0.780	7.270	7.270	4.847	1.170	7.270
0.750	0.877	0.811	0.543	12.262	11.337	7.595	0.842	11.780
1.000	0.703	0.614	0.406	17.474	15.262	10.088	0.652	16.219
1.500	0.503	0.374	0.253	28.160	20.928	14.127	0.423	23.688
2.000	0.391	0.258	0.177	38.873	25.695	17.584	0.305	30.282
3.000	0.276	0.137	0.102	61.828	30.663	22.833	0.175	39.107
4.000	0.213	0.085	0.068	84.617	33.896	26.895	0.112	44.441
5.000	0.168	0.061	0.048	104.226	38.032	29.929	0.080	49.924
6.000	0.132	0.044	0.036	117.866	38.931	32.161	0.058	52.297
7.000	0.104	0.033	0.027	127.174	40.077	33.297	0.045	54.761
8.000	0.085	0.025	0.021	135.238	39.776	33.732	0.035	54.961
9.000	0.065	0.019	0.017	131.089	39.065	33.697	0.026	53.275
10.000	0.054	0.015	0.013	133.250	38.036	33.148	0.022	54.153

Notes:

(1) Design spectra based on MCE (median attenuation) modified for moderate near fault directivity

(2) The San Gregorio Fault (M-7.5) located at 3-kilometer is the controlling fault

(3) The fault parallel direction of the San Gregorio fault can be assumed as the N22^{o}W direction

(4) The fault normal direction of the San Gregorio fault can be assumed as the N68oE direction

(5) The two right columns presents the target rock spectra at 45-degree rotation from the FN/FP as transformed from the FN/FP target spectra based on the elliptical shaking intensity pattern where the FN and FP spectra are defined as the major and minor principal target spectra, respectively and shaking in the intermediate directions are interpolated, based on an elliptical pattern.

TABLE NO. 3

Peak Acceleration, Velocity and Displacement Values of the Startup Time Histories

	PGA (g)	PGV (cm/sec)	PGD (cm)
Set-1 Startup Motion		1992 Landers M-7.3 E.Q., Yermo Fire Station, Forward Rupturing, Distance = 11 Km, Soil Site	
Principal Major (N60^{o}E Direction)	0.23	56.26	48.21
Principal Minor (N30^{o}W Direction)	0.19	17.65	7.75
Vertical	0.14	12.83	5.05
Set-2 Startup Motion		1999 Kocaeli (Turkey) M-7.4 E.Q., Arcelik Record, Forward Rupturing, Distance = 17 Km, Rock Site	
Principal Major (S80^{o}W Direction)	0.14	40.64	44.65
Principal Minor (N10^{o}W Direction)	0.20	19.25	21.18
Vertical	0.08	8.46	9.00
Set-3 Startup Motion		1992 Landers M-7.3 E.Q., Joshua Tree Station, Backward Rupturing, Distance = 12 Km, Soil Site	
Principal Major (S85^{o}W Direction)	0.28	41.63	13.84
Principal Minor (N5^{o}W Direction)	0.28	28.78	9.65
Vertical	0.18	14.96	8.89

Notes:
The principal major and principal minor directions shown in the above table has been computed based on zero cross-correlation coefficients computed using the displacement time history records.
The change in the principal directions computed using velocity time histories can be observed from Figures B-10 through B-12 in Appendix B.

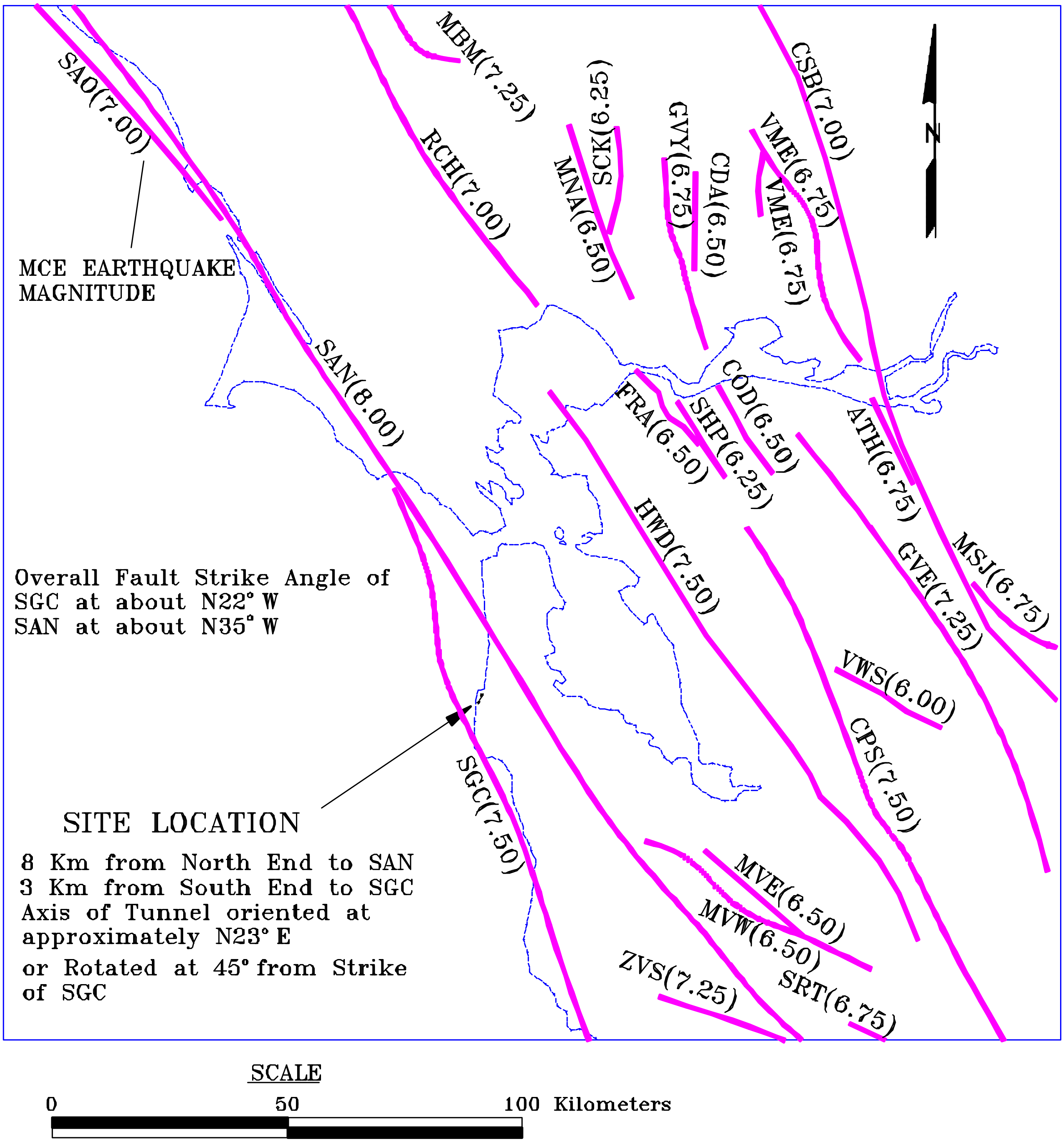
TABLE NO. 4
Peak Acceleration, Velocity and Displacement Values of the Set-1A, Set-2A and Set-3A Spectrum-Compatible Time Histories (Spectrum-Matching in the Fault Axes)

	PGA (g)	PGV (cm/sec)	PGD (cm)
Set-1A			
Fault Normal	0.61	84.1	56.6
Fault Parallel	0.65	52.6	15.3
45-Degree from Fault Normal	0.67	69.2	49.2
135-Degree from Fault Normal	0.60	74.3	32.6
Vertical	0.62	36.7	16.5
Set-2A			
Fault Normal	0.66	98.4	51.1
Fault Parallel	0.67	43.7	24.4
45-Degree from Fault Normal	0.60	78.7	43.8
135-Degree from Fault Normal	0.76	82.1	33.6
Vertical	0.63	36.2	15.8
Set-3A			
Fault Normal	0.66	91.7	50.9
Fault Parallel	0.66	44.5	14.8
45-Degree from Fault Normal	0.62	63.8	42.8
135-Degree from Fault Normal	0.46	87.9	34.4
Vertical	0.58	31.8	13.1

TABLE NO. 5

Peak Acceleration, Velocity and Displacement Values of the Set-1B, Set-2B and Set-3B Spectrum-Compatible Time Histories (Spectrum-Matching in the Tunnel Axes, or 45-Degree from Fault Axes)

	PGA (g)	PGV (cm/sec)	PGD (cm)
Set-1B			
Fault Normal	0.58	60.2	30.5
Fault Parallel	0.75	46.6	12.1
45-Degree from Fault Normal	0.66	55.6	28.5
135-Degree from Fault Normal	0.66	56.8	26.2
Vertical	0.62	36.7	16.5
Set-2B			
Fault Normal	0.59	66.3	28.9
Fault Parallel	0.71	48.6	13.8
45-Degree from Fault Normal	0.67	52.6	25.5
135-Degree from Fault Normal	0.66	61.1	24.3
Vertical	0.63	36.2	15.8
Set-3B			
Fault Normal	0.57	61.2	25.1
Fault Parallel	0.59	39.8	11.7
45-Degree from Fault Normal	0.66	44.1	21.3
135-Degree from Fault Normal	0.61	69.1	20.4
Vertical	0.58	31.8	13.1



CAPTIONS FOR SELECTED FAULTS: EXTRACTED FROM MUALCHIN, JULY, 1996
SAN– San Andreas North, HWD– Hayward Fault, SGC– San Gregorio Fault
RCH– Roger's Creek Healdsburg Fault, GVY– Green Valley Fault,
CPS– Calaveras Fault, GVE– Greenville Fault

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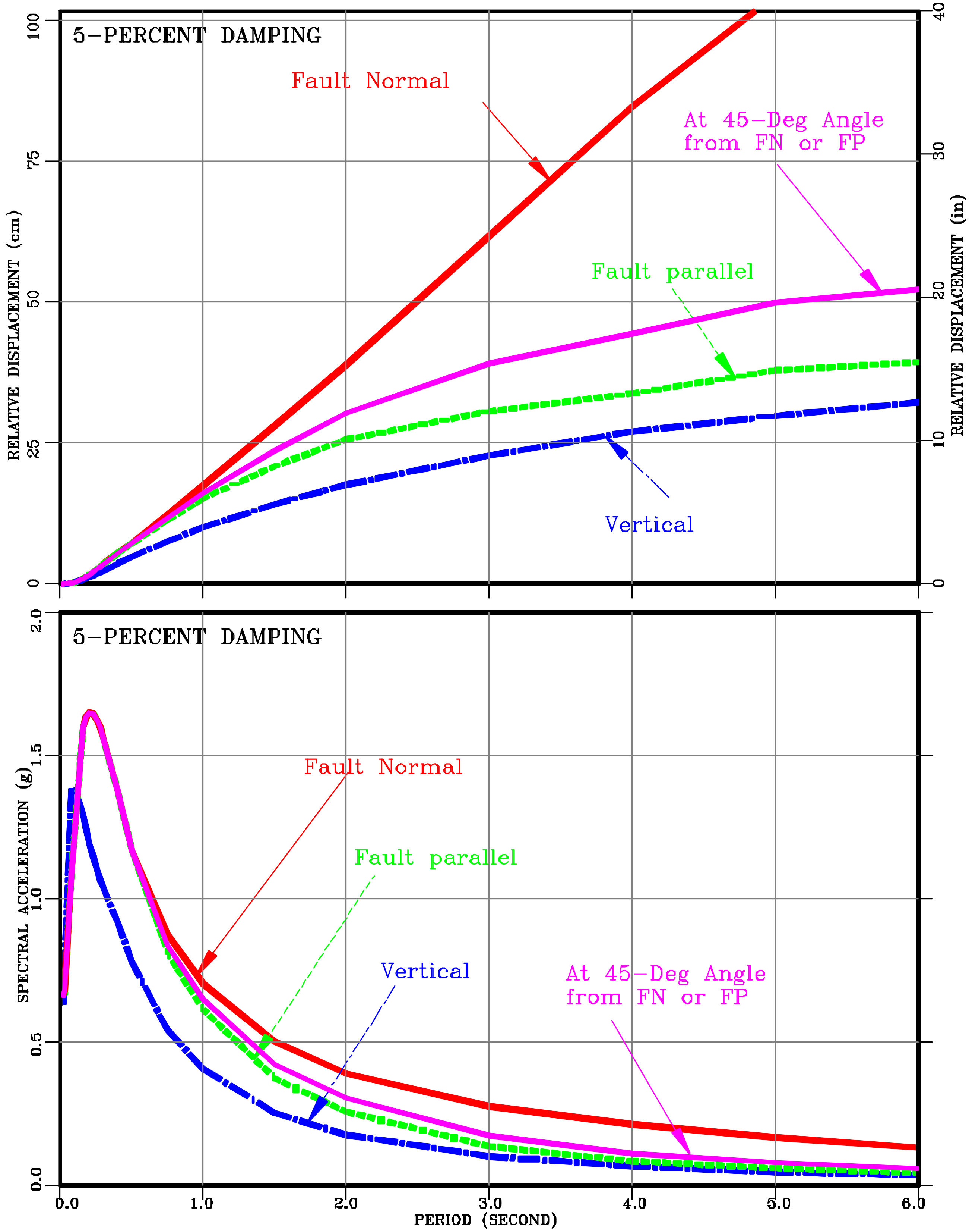
DEVIL'S SLIDE TUNNELS

EMI Project No.: 01–120 Date: 8/20/01

FAULT MAP AROUND PROJECT SITE

FIGURE 1



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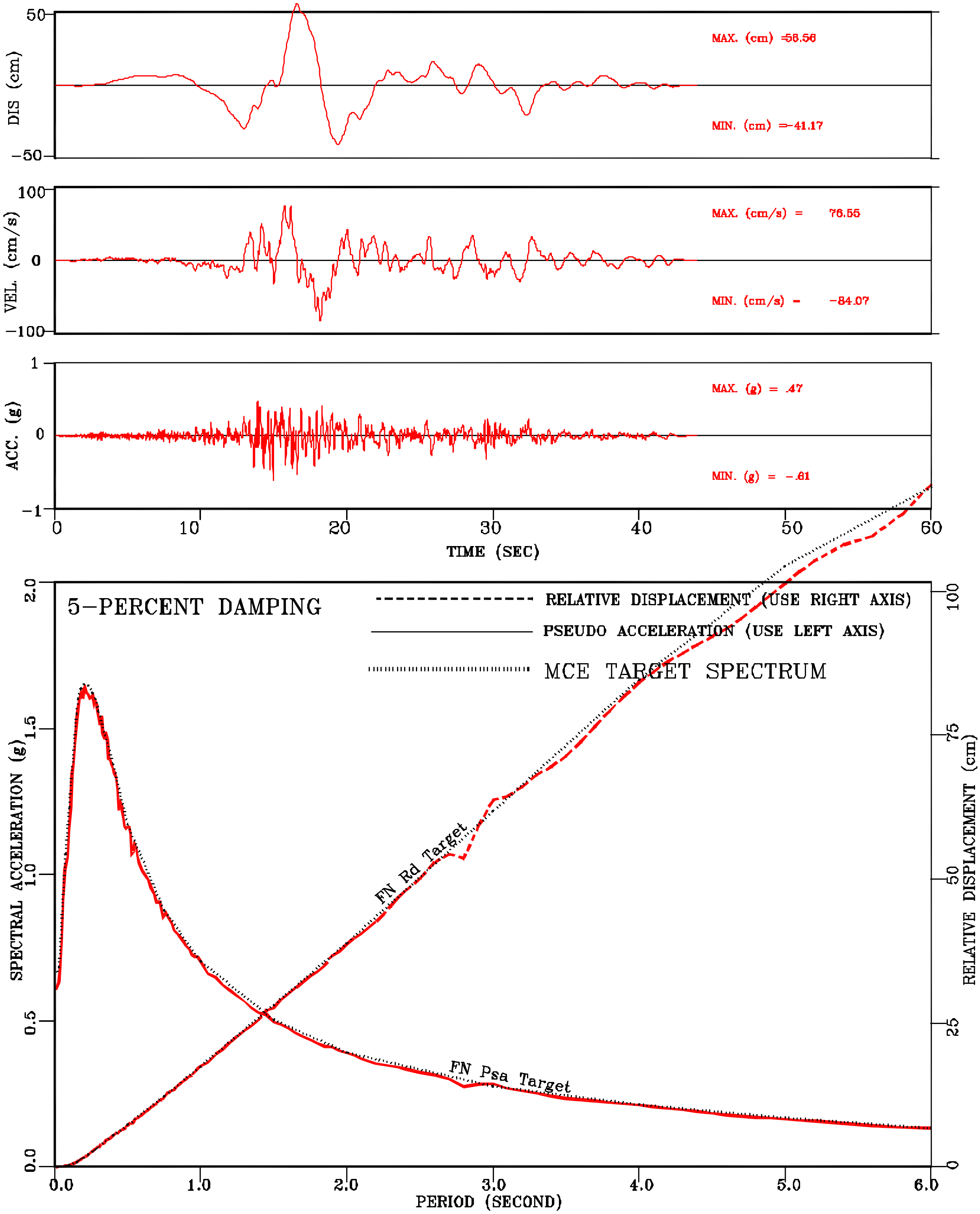
DEVIL'S SLIDE TUNNELS

EMI Project No.: 01-119 | Date: 8/20/01

REFERENCE TARGET ROCK SPECTRA

Figure 2



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DEVIL'S SLIDE TUNNELS

EMI Project No.: 01-119 | Date: 8/20/01

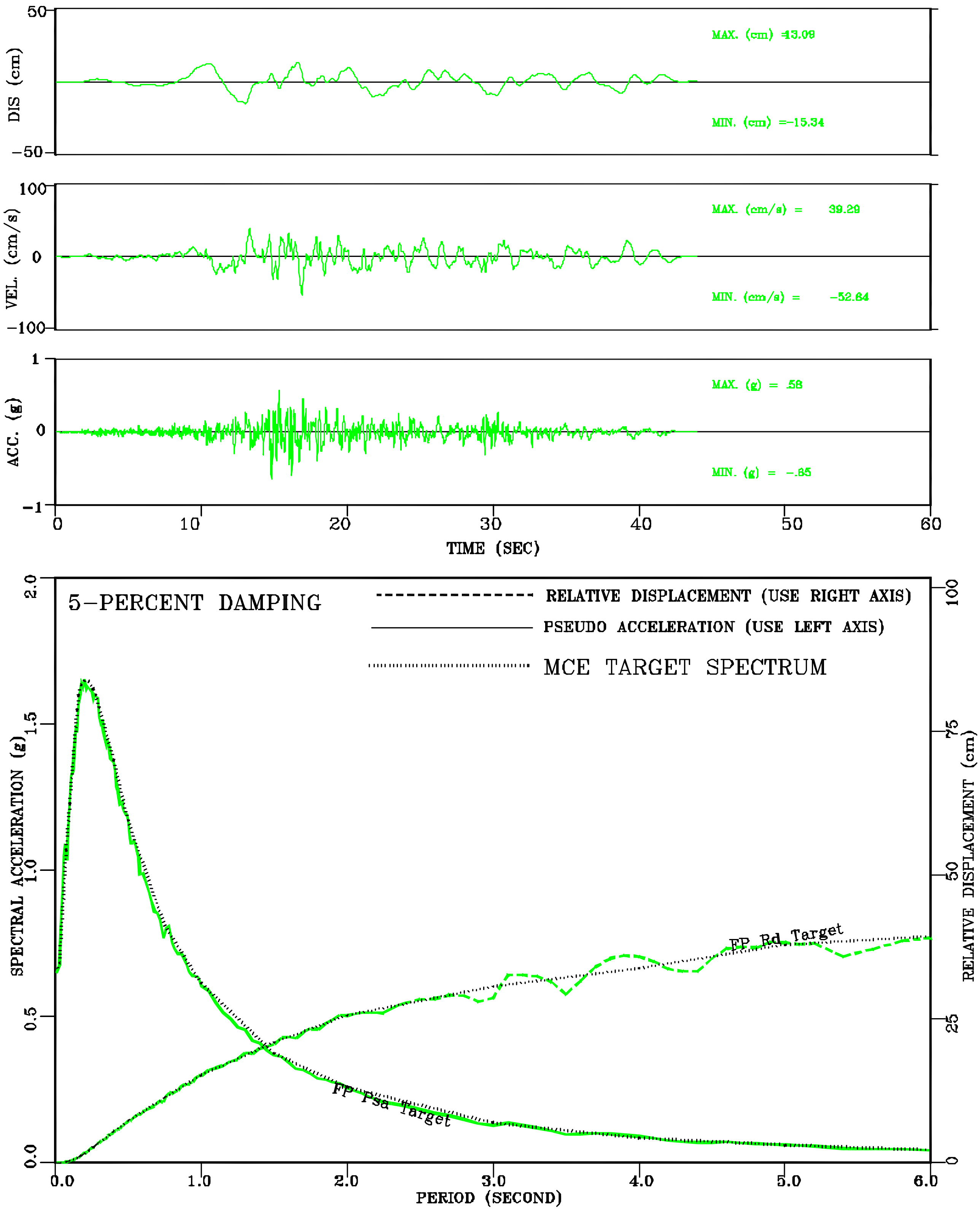
MCE SET-1A ROCK MOTION

MODIFIED FROM 1992 LANDERS YERMO RECORD

Motion Matched to FN/FP Spectra

FAULT NORMAL COMPONENT

Figure 3



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MCE SET-1A ROCK MOTION

MODIFIED FROM 1992 LANDERS YERMO RECORD

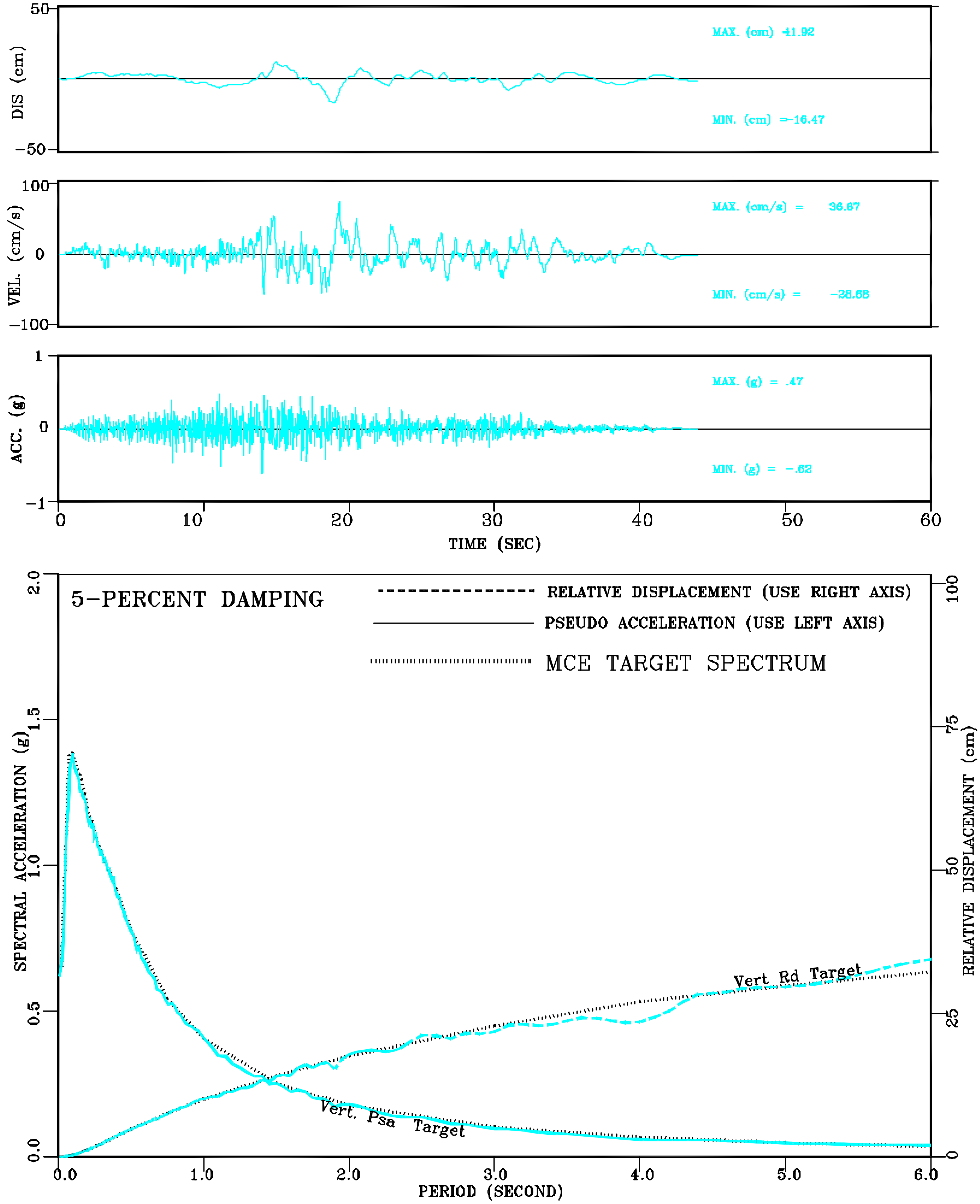
Motion Matched to FN/FP Spectra

DEVIL'S SLIDE TUNNELS

FAULT PARALLEL COMPONENT

EMI Project No.: 01-119 | Date:8/20/01

Figure 4



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DEVIL'S SLIDE TUNNELS

EMI Project No.: 01-119 | Date:8/20/01

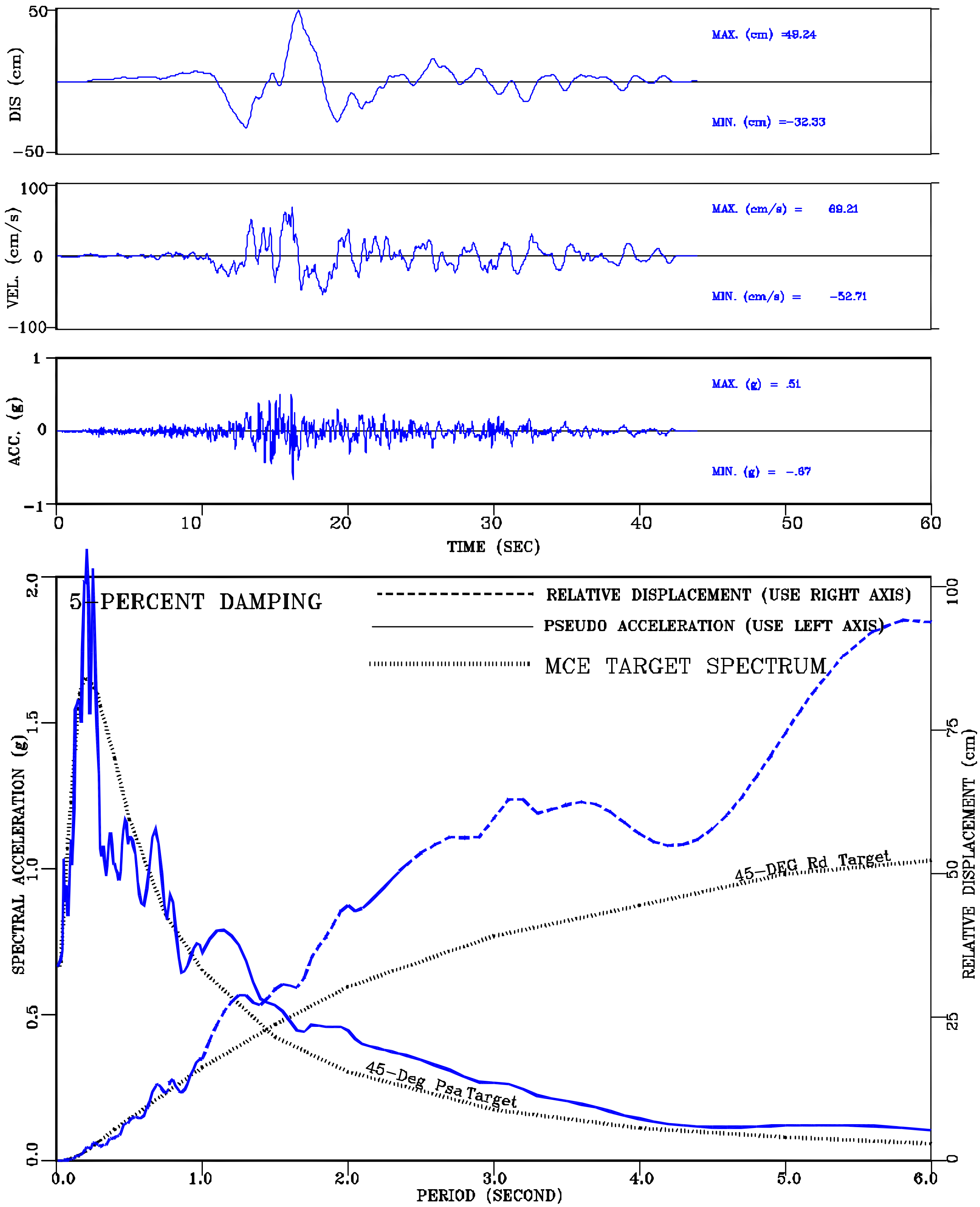
MCE SET-1A ROCK MOTION

MODIFIED FROM 1992 LANDERS YERMO RECORD

Motion Matched to FN/FP Spectra

VERTICAL (UP) COMPONENT

Figure 5



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DEVIL'S SLIDE TUNNELS

EMI Project No.: 01-119 | Date: 8/20/01

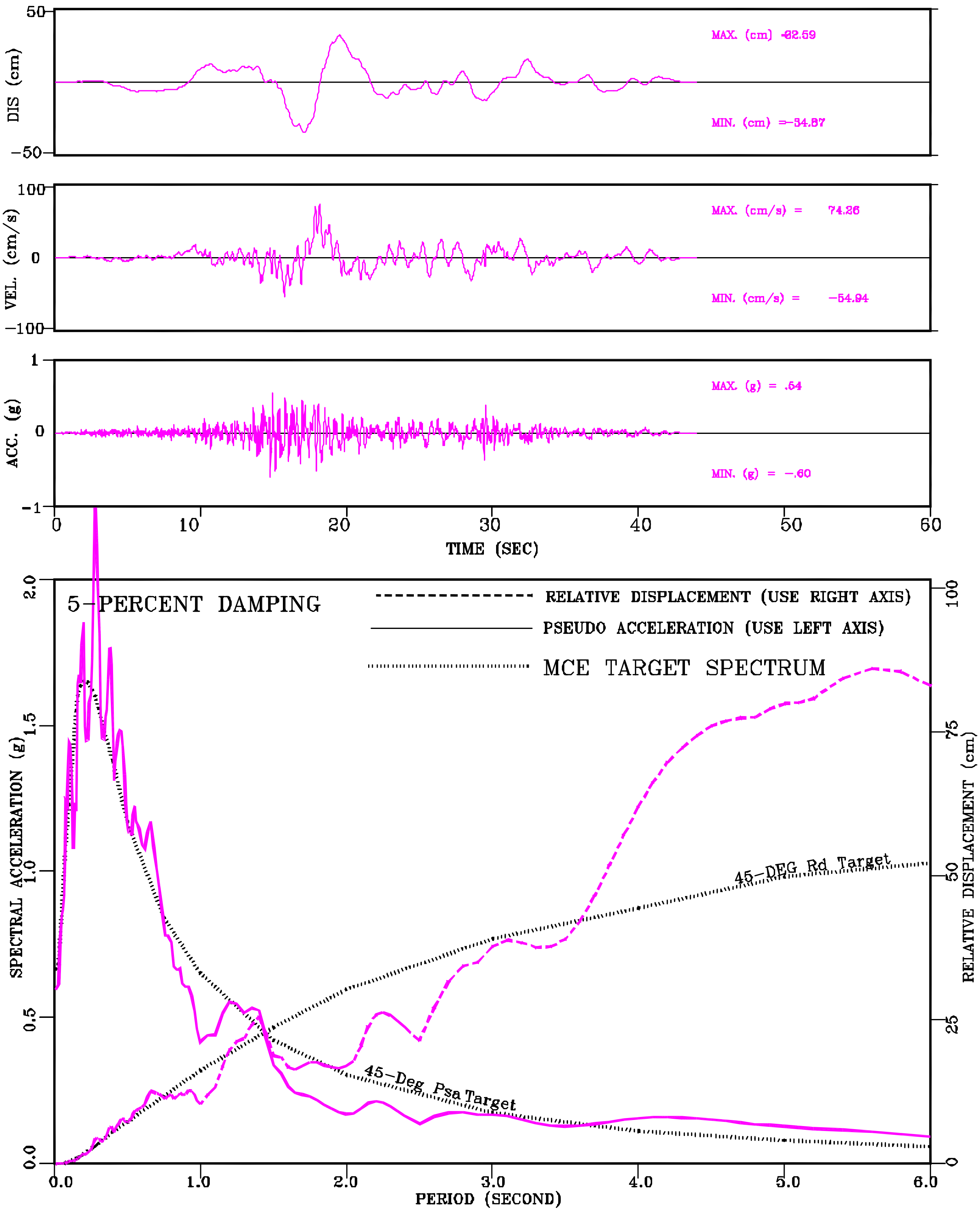
MCE SET-1A ROCK MOTION

MODIFIED FROM 1992 LANDERS YERMO RECORD

Motion Matched to FN/FP Spectra

45-Deg Counter Clockwise wrt FN

Figure 6



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DEVIL'S SLIDE TUNNELS

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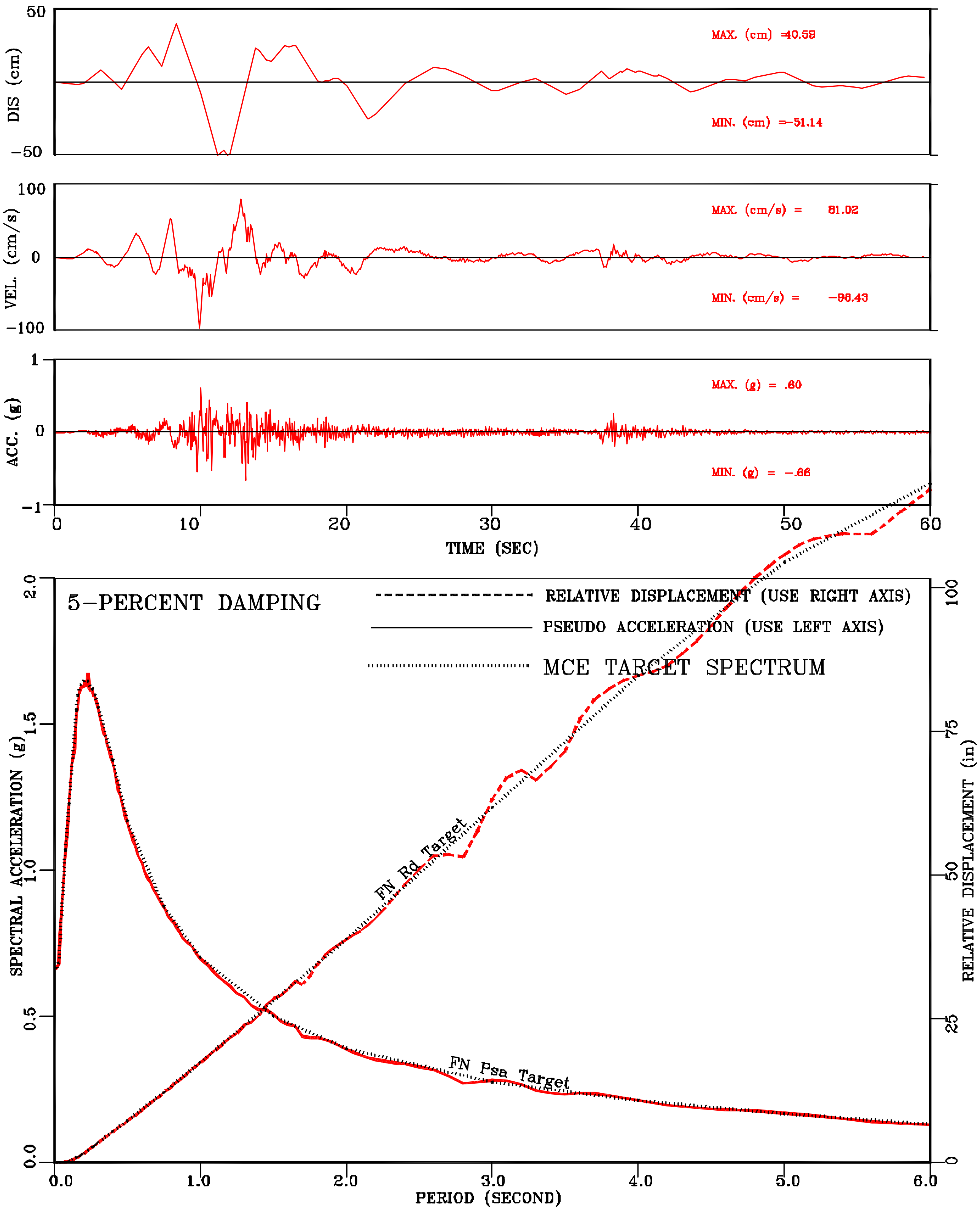
MCE SET-1A ROCK MOTION
MODIFIED FROM 1992 LANDERS YERMO RECORD
Motion Matched to FN/FP Spectra
135-Deg Counter-Clockwise wrt FN

FIGURE-7



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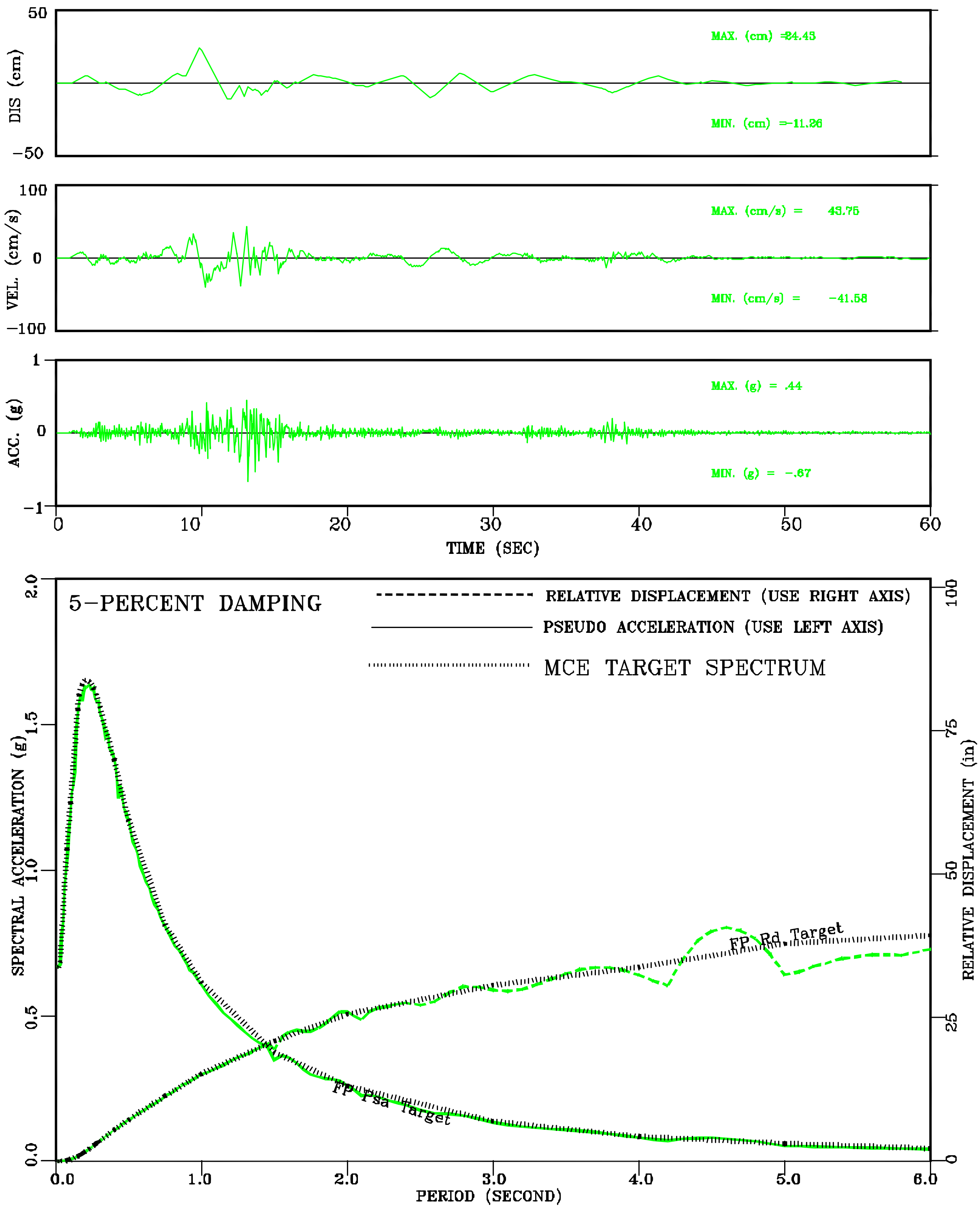
DEVIL'S SLIDE TUNNELS

EMI Project No.: 01-119 | Date:8/20/01

MCE SET-2A ROCK MOTION
MODIFIED FROM 1999 TURKEY ARC RECORD
Motions Matched to FN/FP Spectra
FAULT NORMAL COMPONENT

Figure 8



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DEVIL'S SLIDE TUNNELS

EMI Project No.: 01-119 | Date: 8/20/01

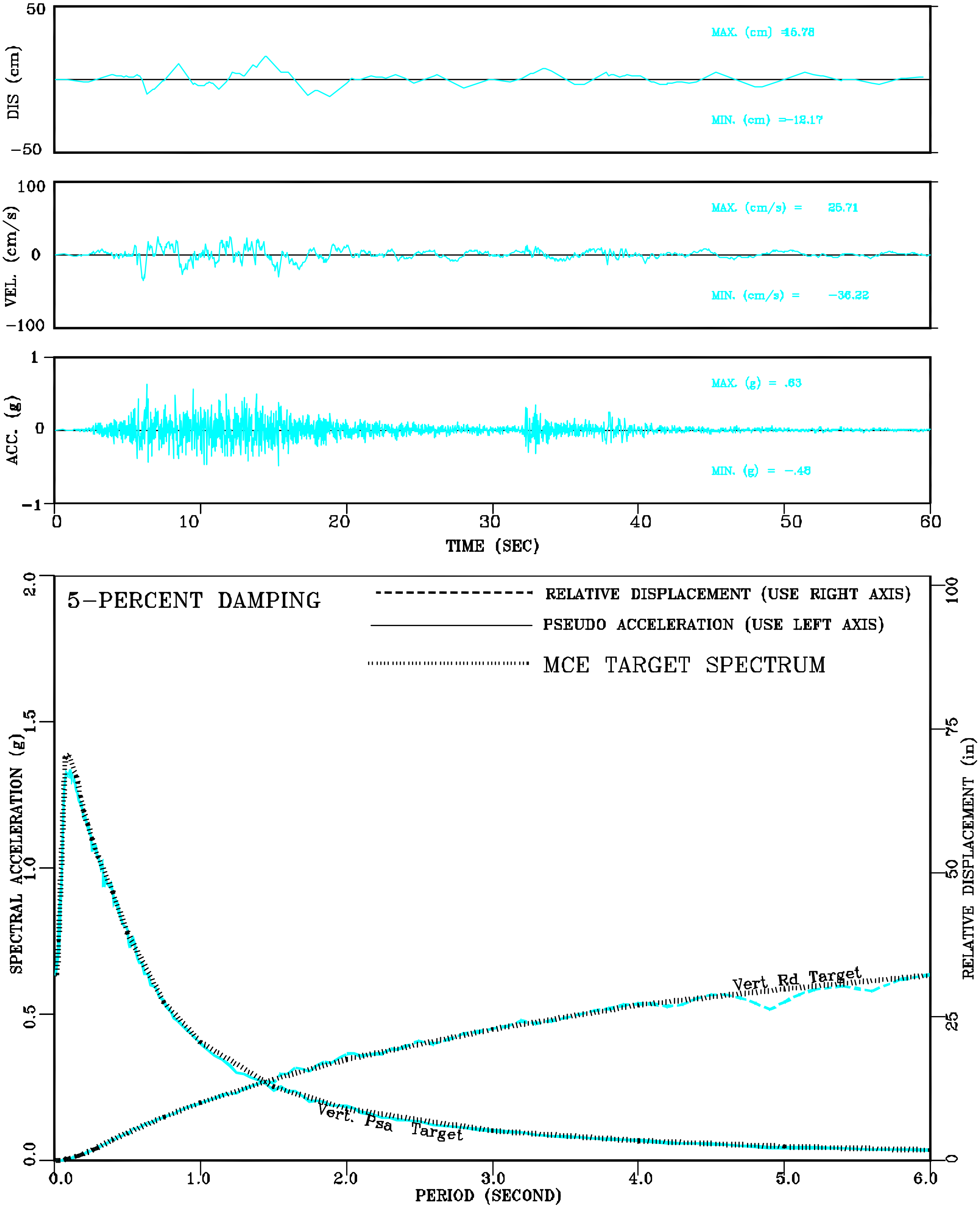
MCE SET-2A ROCK MOTION

MODIFIED FROM 1999 TURKEY ARC RECORD

Motions Matched to FN/FP Spectra

FAULT PARALLEL COMPONENT

Figure 9



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DEVIL'S SLIDE TUNNELS

EMI Project No.: 01-119 | Date: 8/20/01

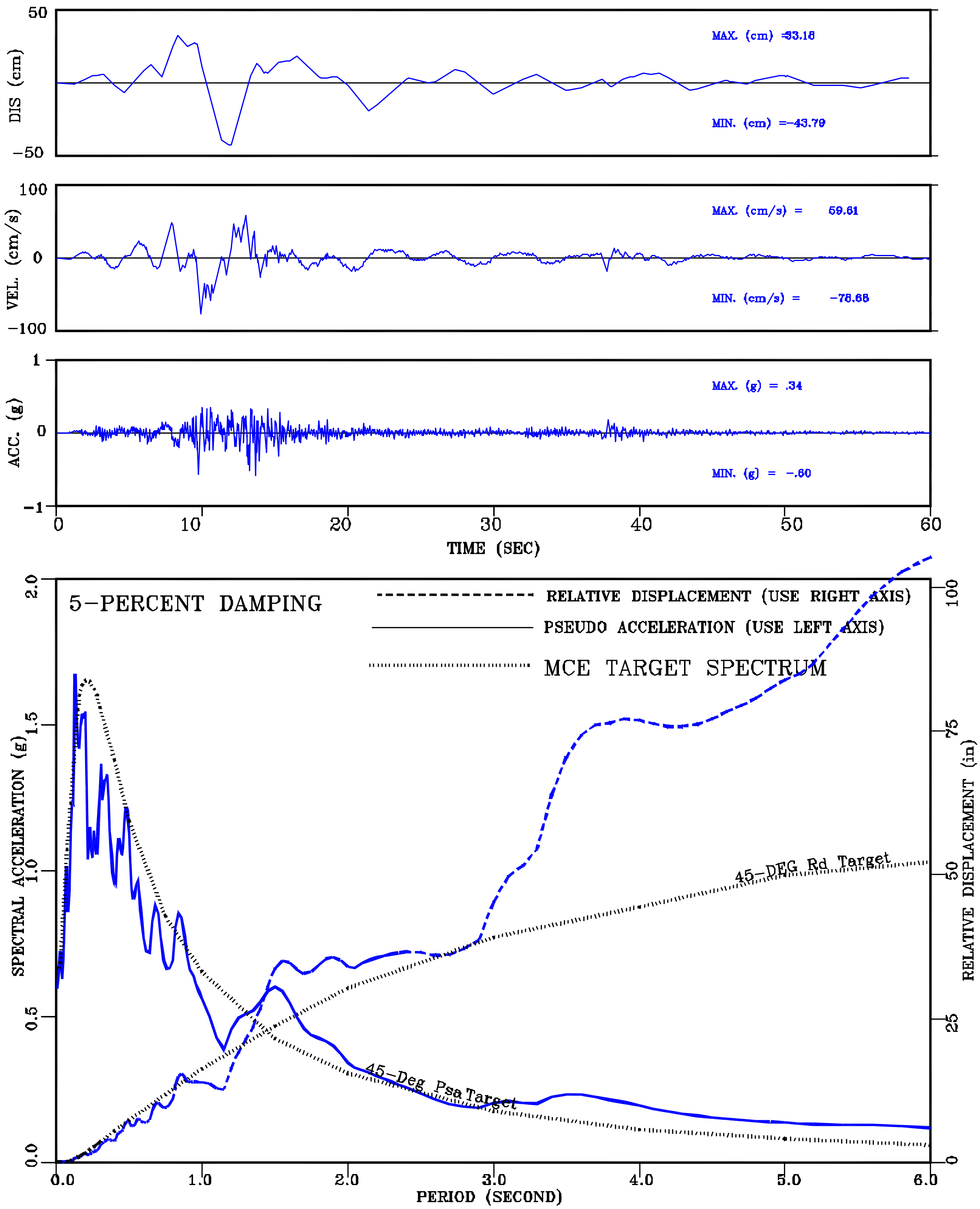
MCE SET-2A ROCK MOTION

MODIFIED FROM 1999 TURKEY ARC RECORD

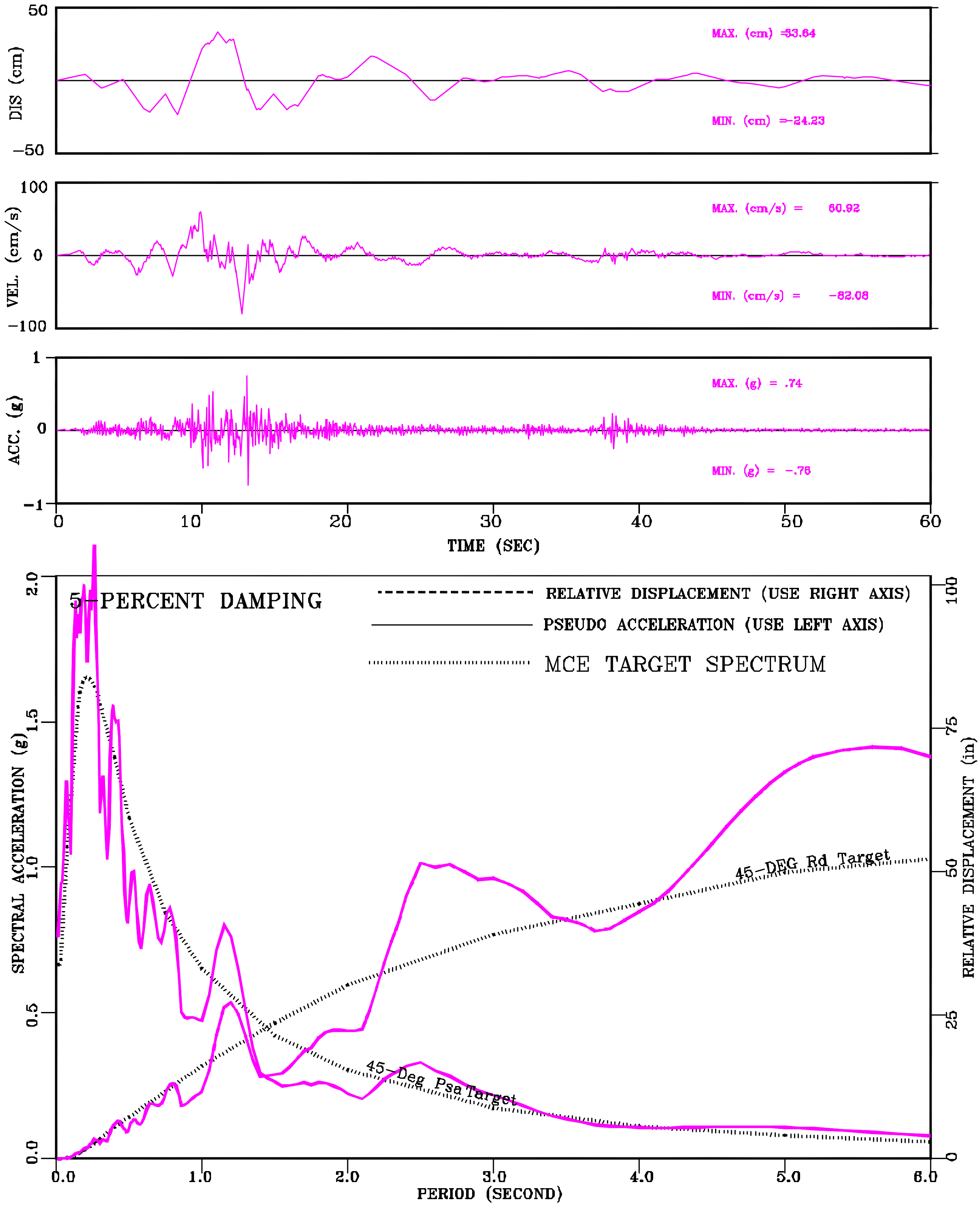
Motions Matched to FN/FP Spectra

VERTICAL (UP) COMPONENT

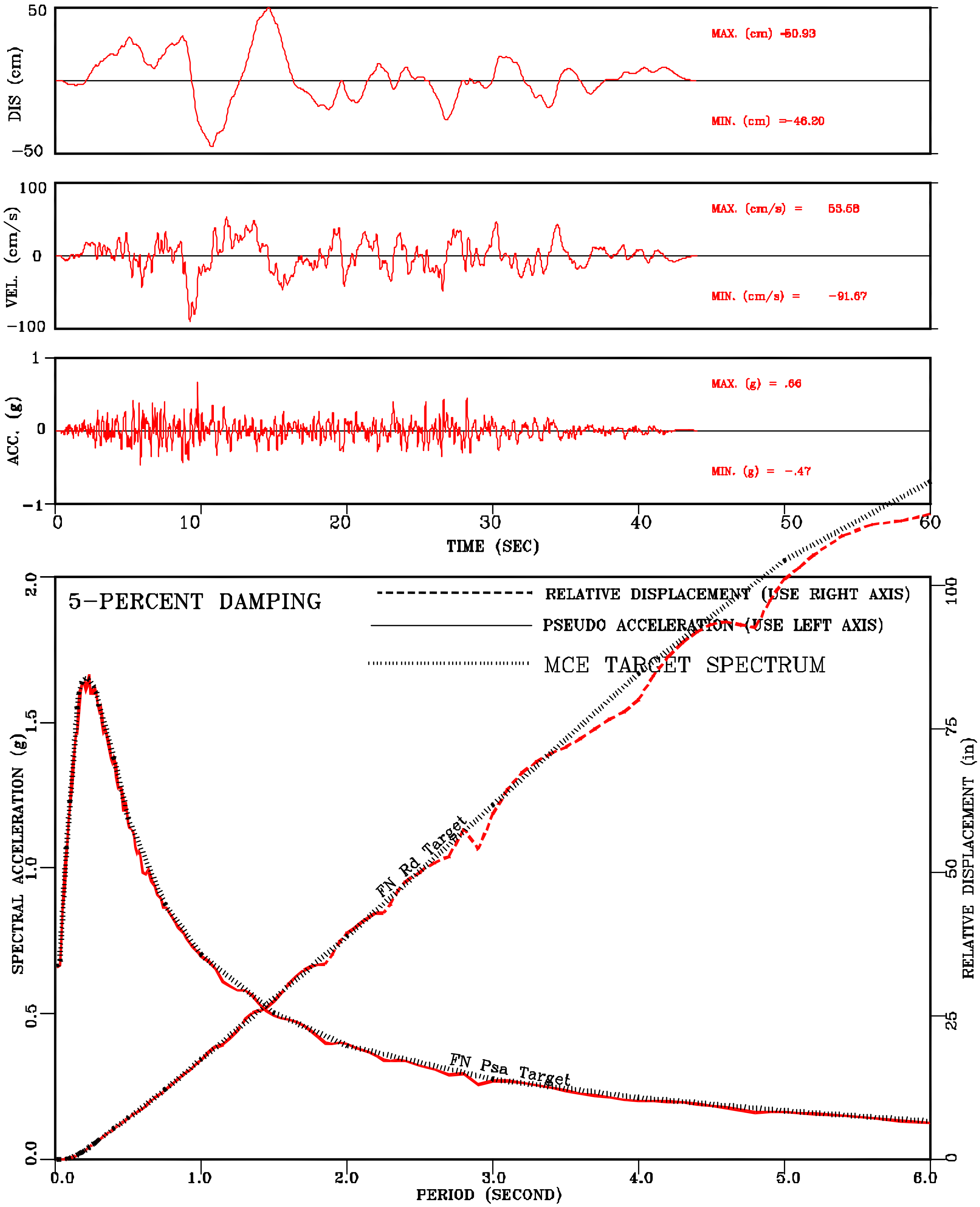
Figure 10



Earth Mechanics, Inc. Geotechnical and Earthquake Engineering	MCE SET-2A ROCK MOTION MODIFIED FROM 1999 TURKEY ARC RECORD Motions Matched to FN/FP Spectra 45-Deg Counter Clockwise from FN
DEVIL'S SLIDE TUNNELS	
EMI Project No.: 01-119 / Date:8/20/01	Figure 11



Earth Mechanics, Inc. Geotechnical and Earthquake Engineering	MCE SET-2A ROCK MOTION MODIFIED FROM 1999 TURKEY ARC RECORD Motions Matched to FN/FP Spectra 135-Deg Counter Clockwise from FN Figure 12
DEVIL'S SLIDE TUNNELS	
EMI Project No.: 01-119 / Date: 8/20/01	



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DEVIL'S SLIDE TUNNELS

EMI Project No.: 01-119 | Date: 8/20/01

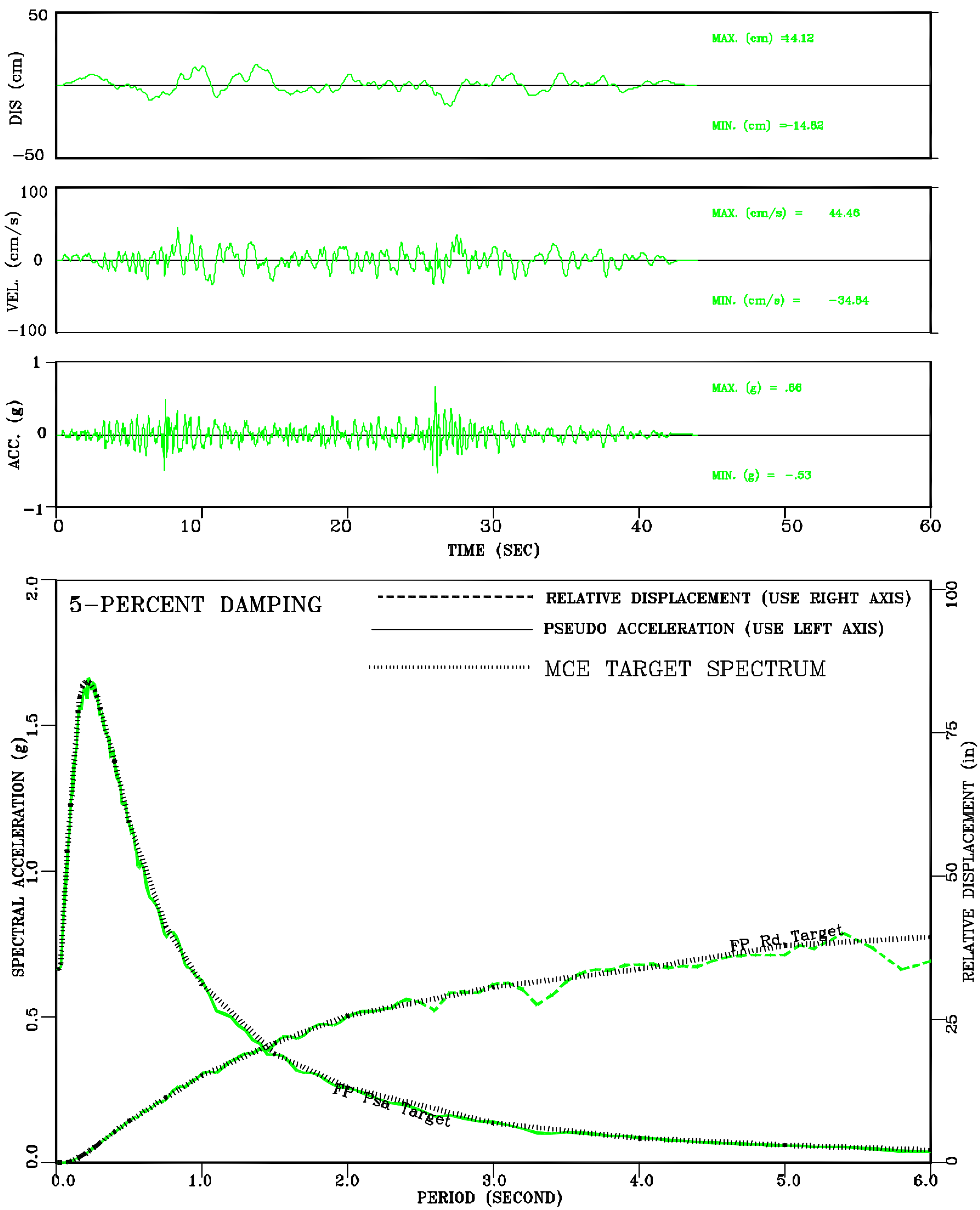
MCE SET-3A ROCK MOTION

MODIFIED FROM 1992 LANDERS JOSHUA TREE RECORD

Motions Matched to FN/FP Spectra

FAULT NORMAL COMPONENT

Figure 13



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DEVIL'S SLIDE TUNNELS

EMI Project No.: 01-119 | Date: 8/20/01

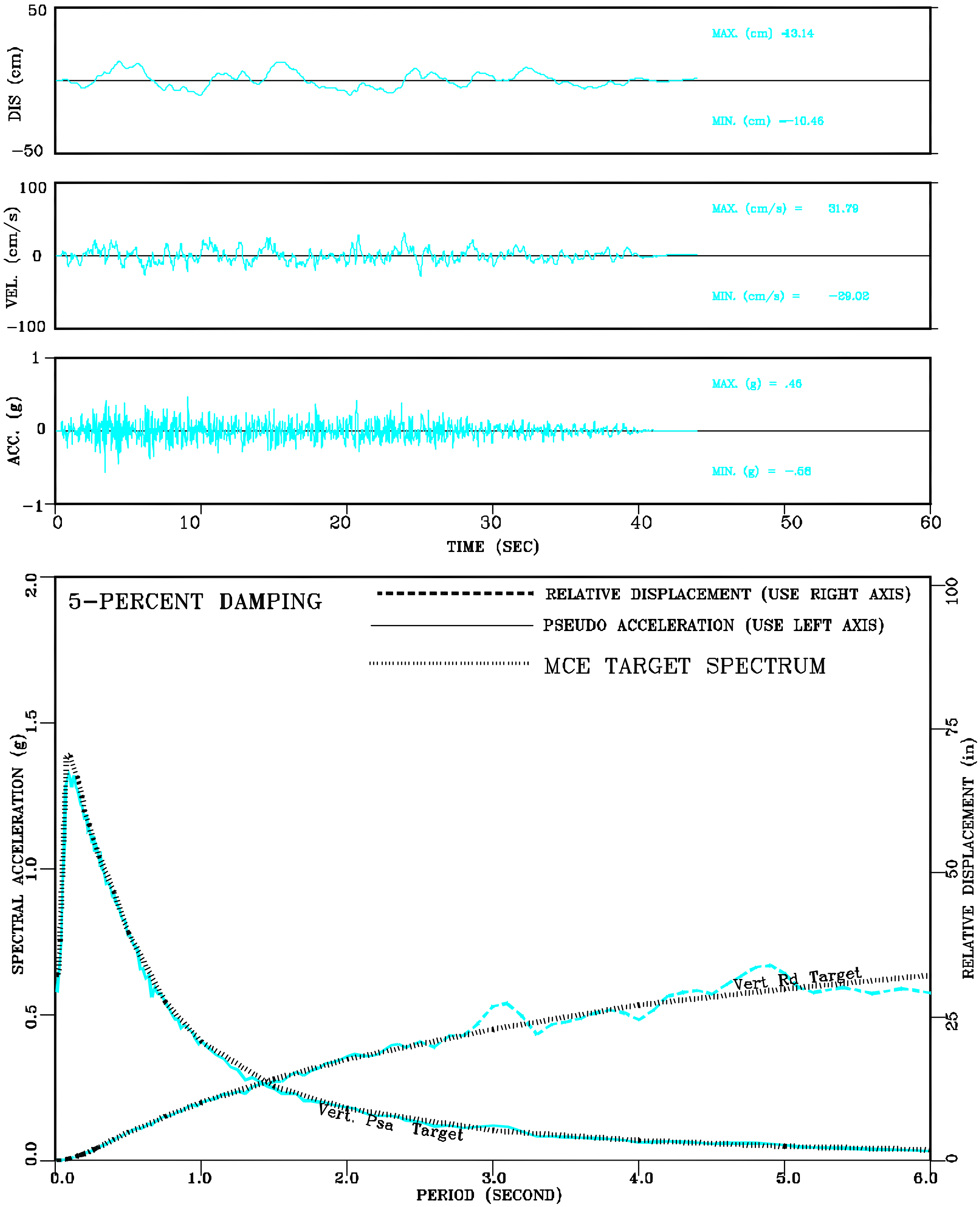
MCE SET-3A ROCK MOTION

MODIFIED FROM 1992 LANDERS JOSHUA TREE RECORD

Motions Matched to FN/FP Spectra

FAULT PARALLEL COMPONENT

Figure 14



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DEVIL'S SLIDE TUNNELS

EMI Project No.: 01-119 | Date: 8/20/01

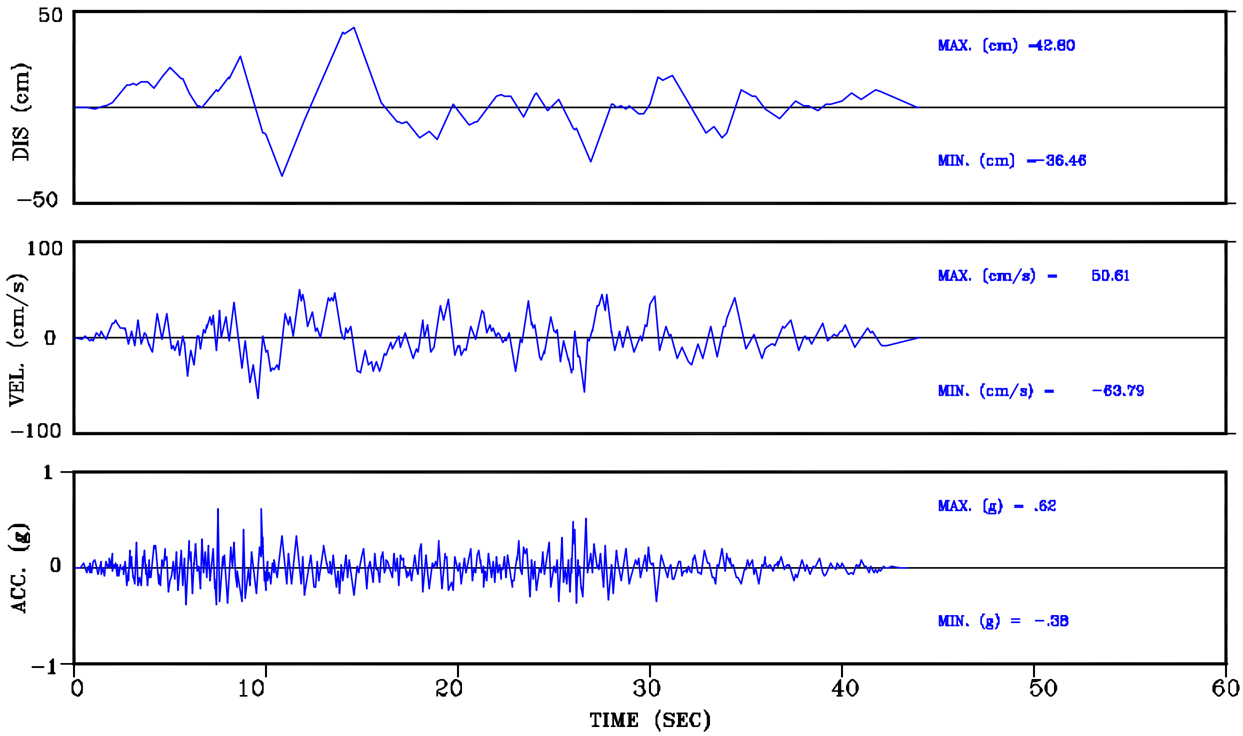
MCE SET-3A ROCK MOTION

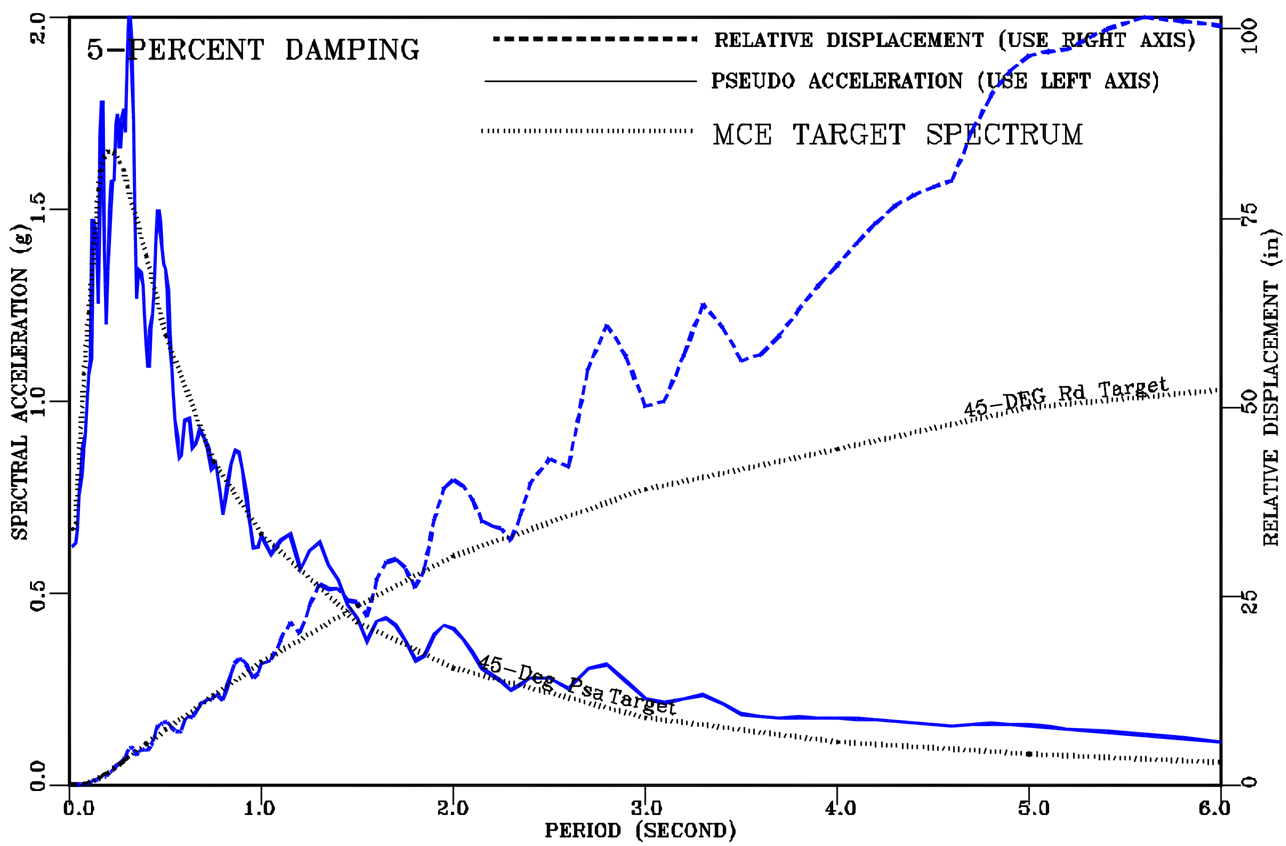
MODIFIED FROM 1992 LANDERS JOSHUA TREE RECORD

Motions Matched to FN/FP Spectra

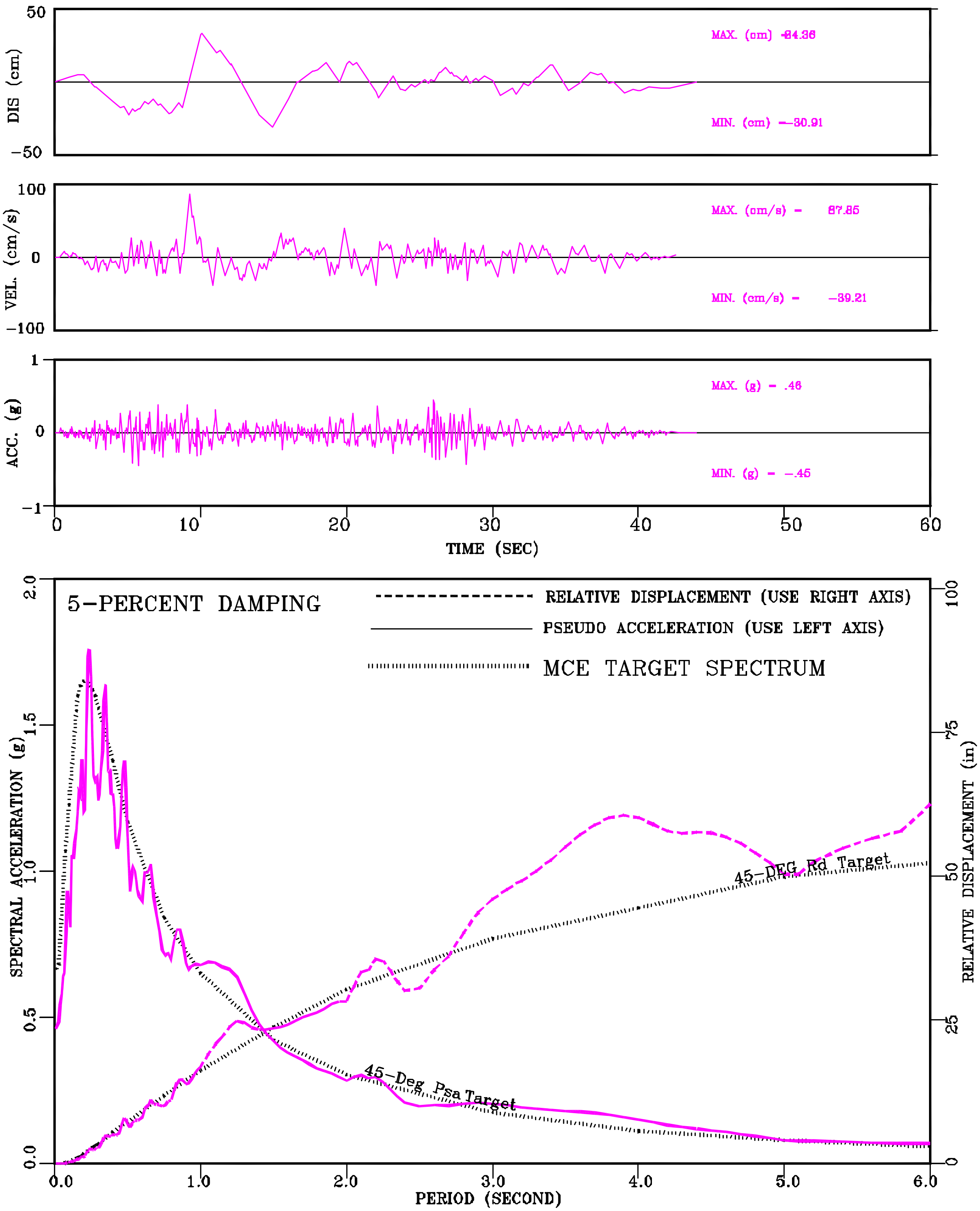
VERTICAL (UP) COMPONENT

Figure 15





Earth Mechanics, Inc. Geotechnical and Earthquake Engineering	MCE SET-3A ROCK MOTION MODIFIED FROM 1992 LANDERS JOSHUA TREE RECORD Motions Matched to FN/FP Spectra 45-Deg Counter Clockwise from FN
DEVIL'S SLIDE TUNNELS	
EMI Project No.: 01-119 Date:8/20/01	Figure 16



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DEVIL'S SLIDE TUNNELS

EMI Project No.: 01-119 | Date: 8/20/01

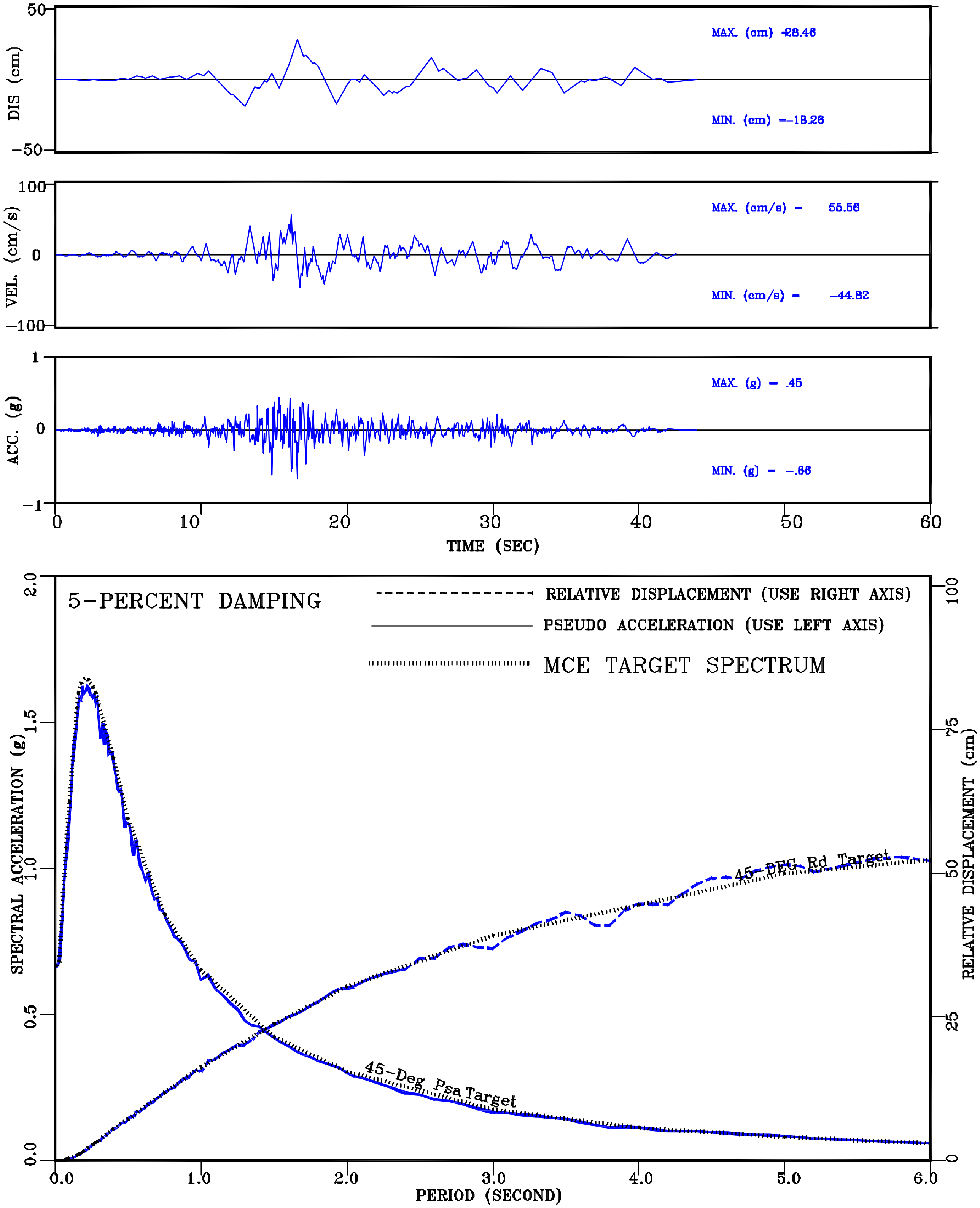
MCE SET-3A ROCK MOTION

MODIFIED FROM 1992 LANDERS JOSHUA TREE RECORD

Motions Matched to FN/FP Spectra

135-Degree Counter Clockwise from FN

Figure 17



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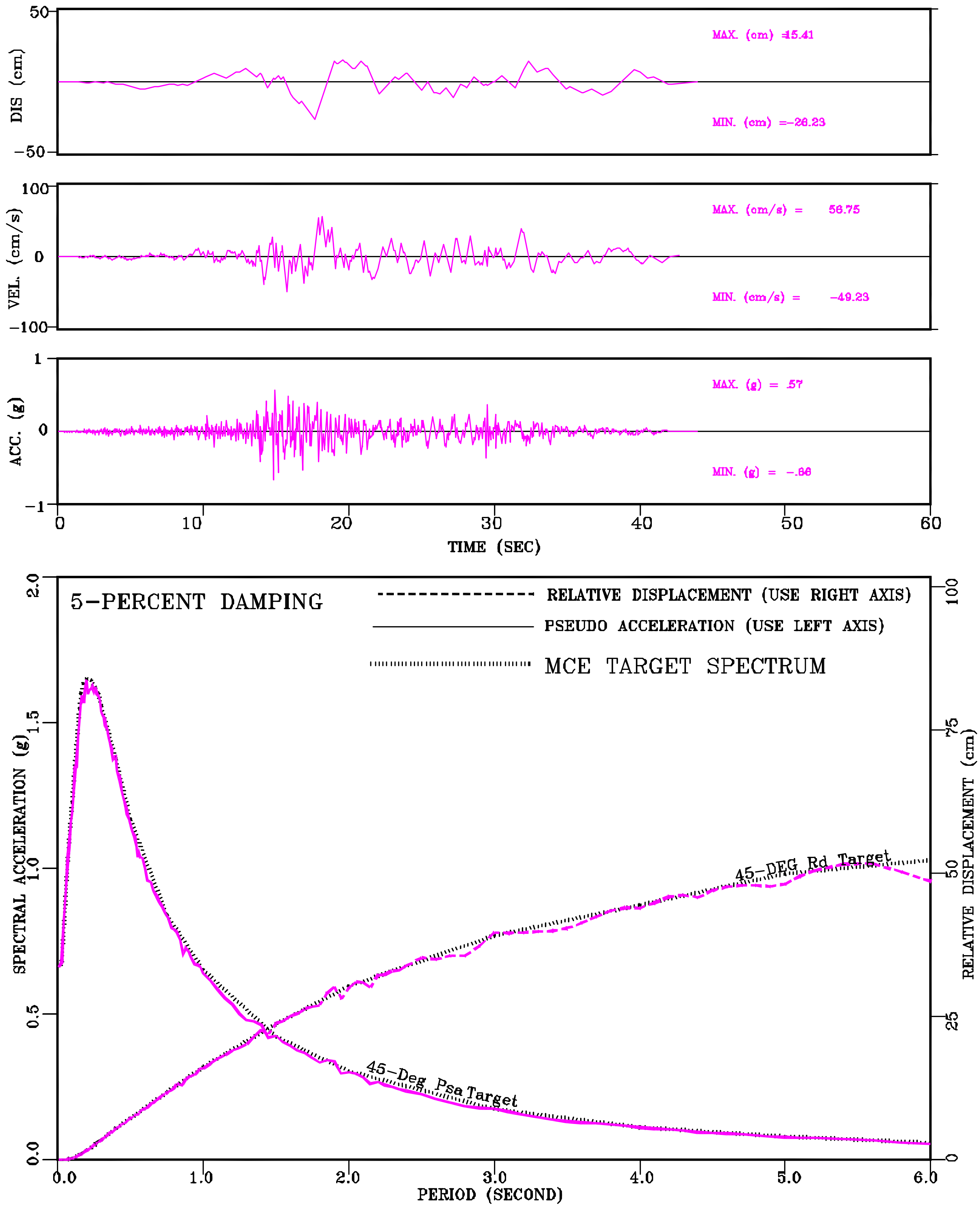
DEVIL'S SLIDE TUNNELS

EMI Project No.: 01-119 | Date: 8/20/01

MCE SET-1B ROCK MOTION
MODIFIED FROM 1992 LANDERS YERMO RECORD
Motions Matched to 45-Deg. Spectrum
45-Deg. Counter Clockwise wrt FN

Figure 18



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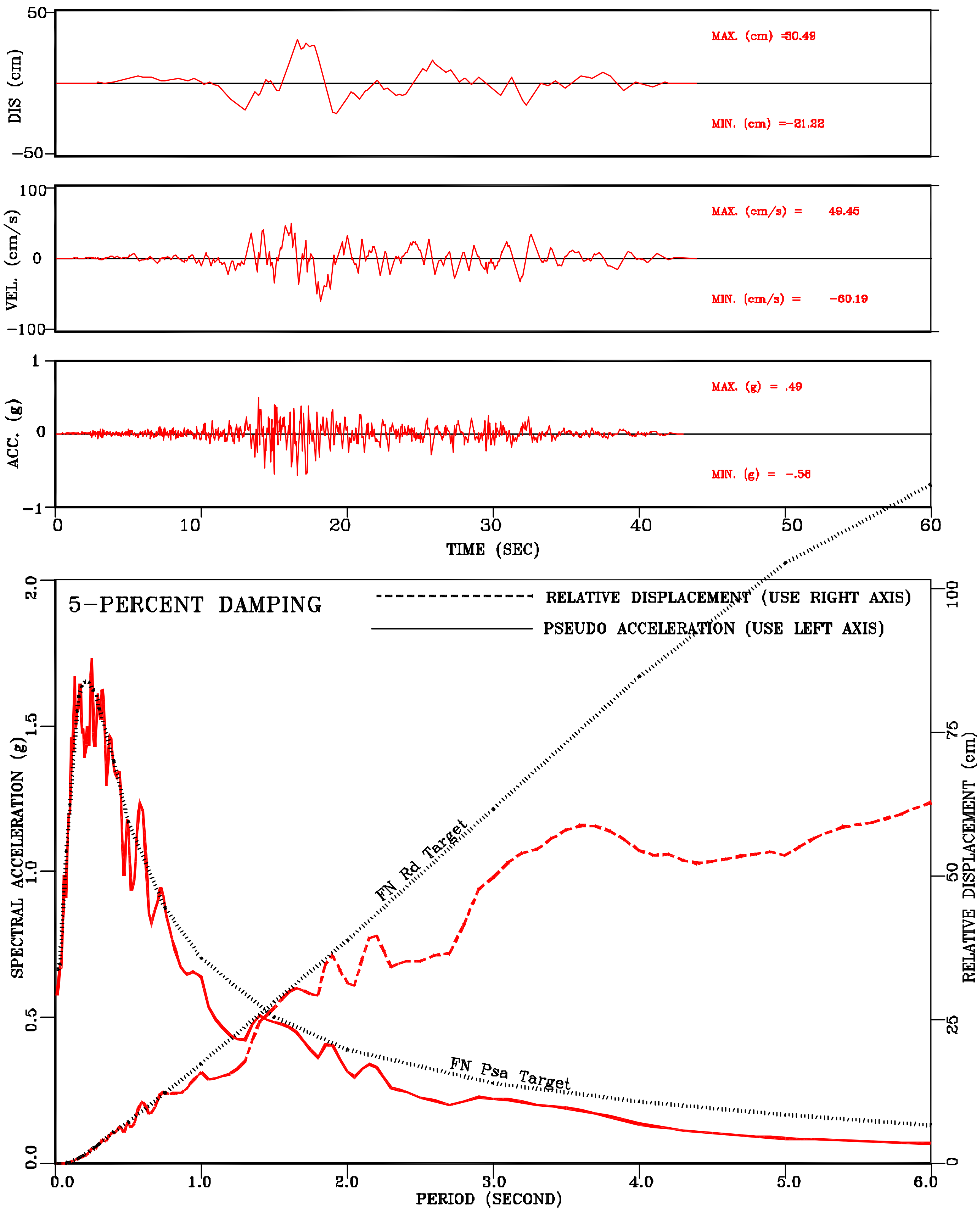
DEVIL'S SLIDE TUNNELS

EMI Project No.: 01-119 | Date:8/20/01

MCE SET-1B ROCK MOTION
MODIFIED FROM 1992 LANDERS YERMO RECORD
Motions Matched to 45-Deg. Spectrum
135-Deg Counter-Clockwise wrt FN

FIGURE-19



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DEVIL'S SLIDE TUNNELS

EMI Project No.: 01-119 | Date:8/20/01

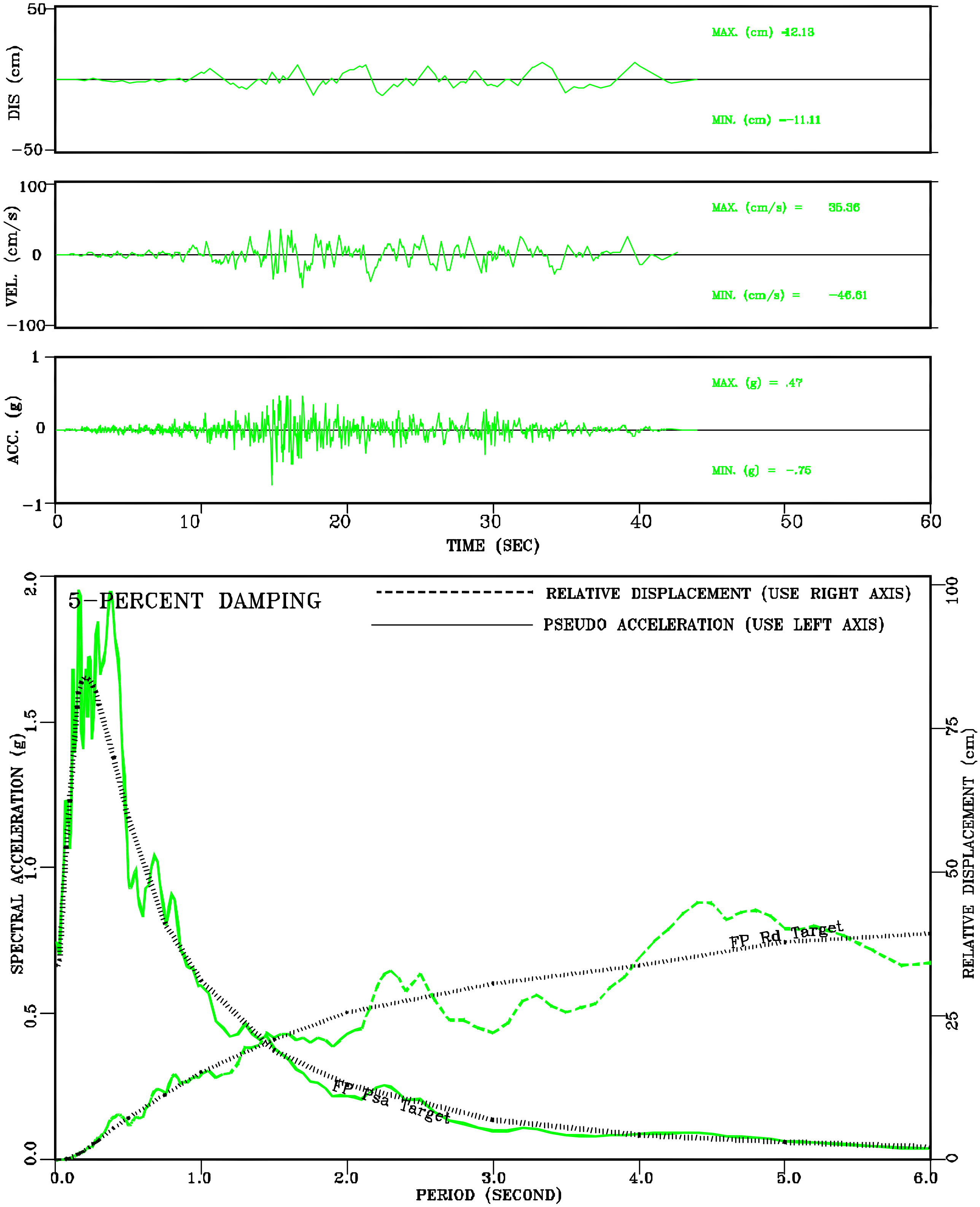
MCE SET-1B ROCK MOTION

MODIFIED FROM 1992 LANDERS YERMO RECORD

Motions Matched to 45-Deg. Spectrum

FAULT NORMAL COMPONENT

Figure 20



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DEVIL'S SLIDE TUNNELS

EMI Project No.: 01-119 | Date: 8/20/01

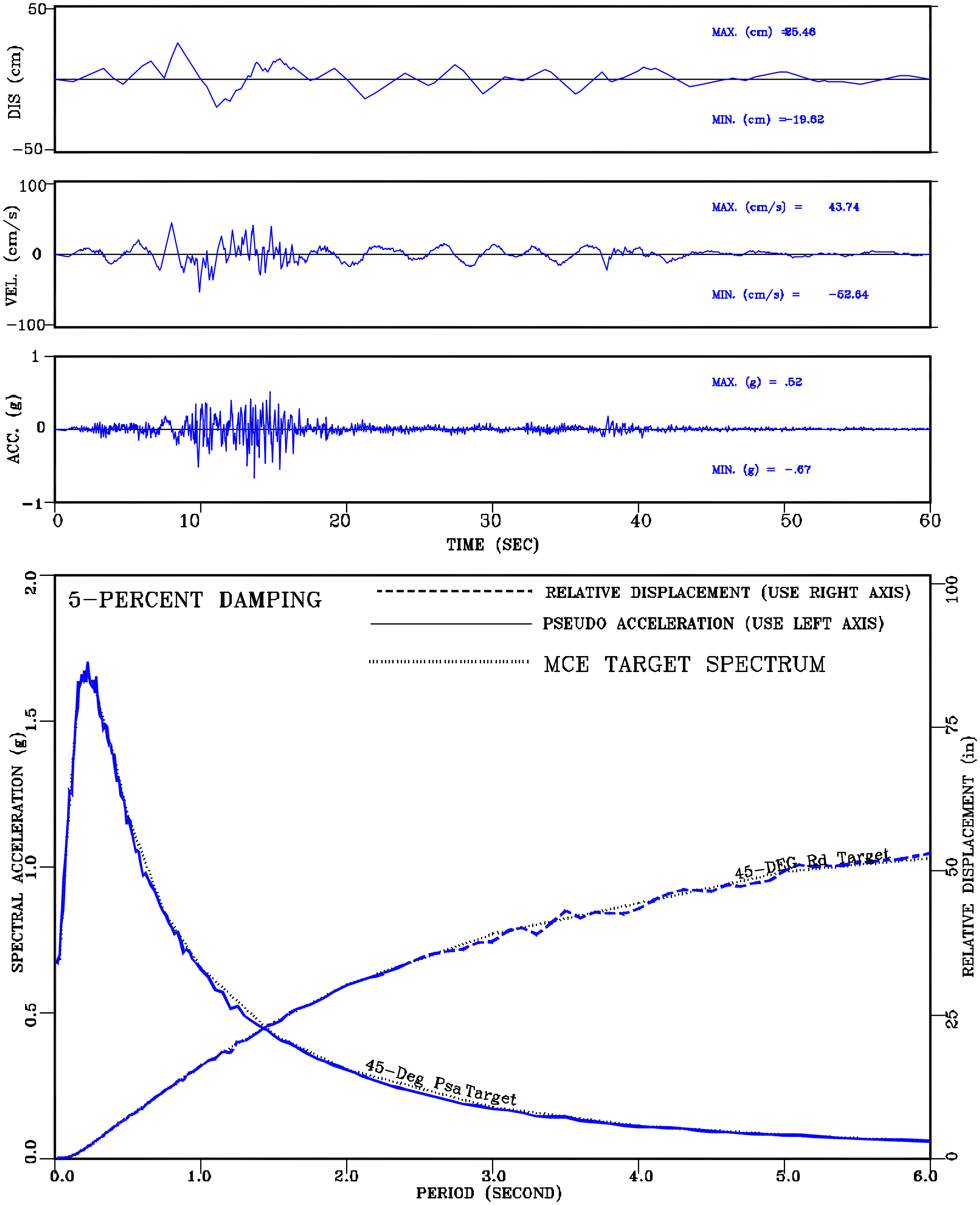
MCE SET-1B ROCK MOTION

MODIFIED FROM 1992 LANDERS YERMO RECORD

Motions Matched to 45-Deg. Spectrum

FAULT PARALLEL COMPONENT

Figure 21



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DEVIL'S SLIDE TUNNELS

EMI Project No.: 01-119 | Date: 8/20/01

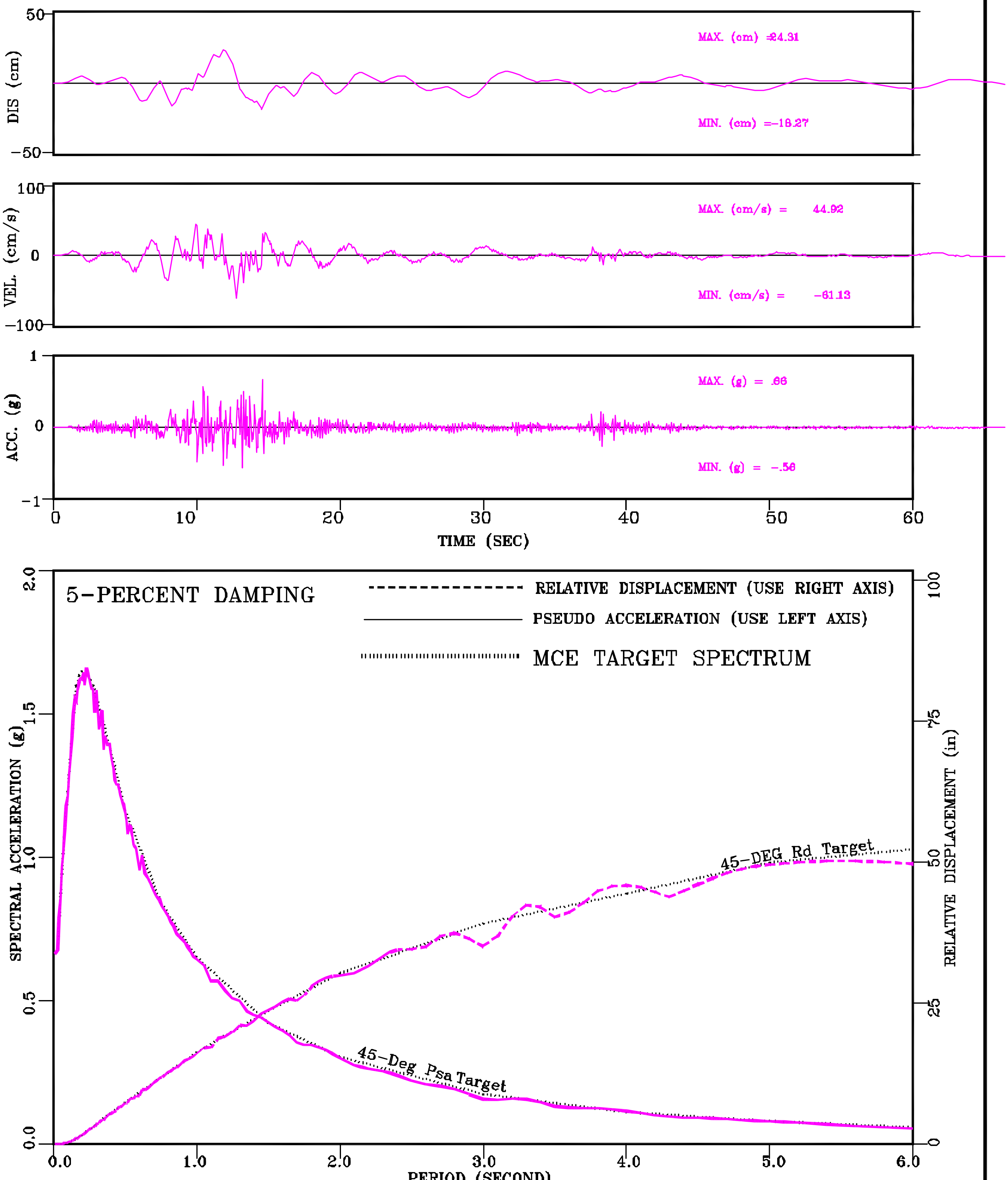
MCE SET-2B ROCK MOTION

Modified from 1999 Turkey ARC Record

Motions Matched to 45-Deg. Spectrum

45-Deg. Counter Clockwise from FN

Figure 22



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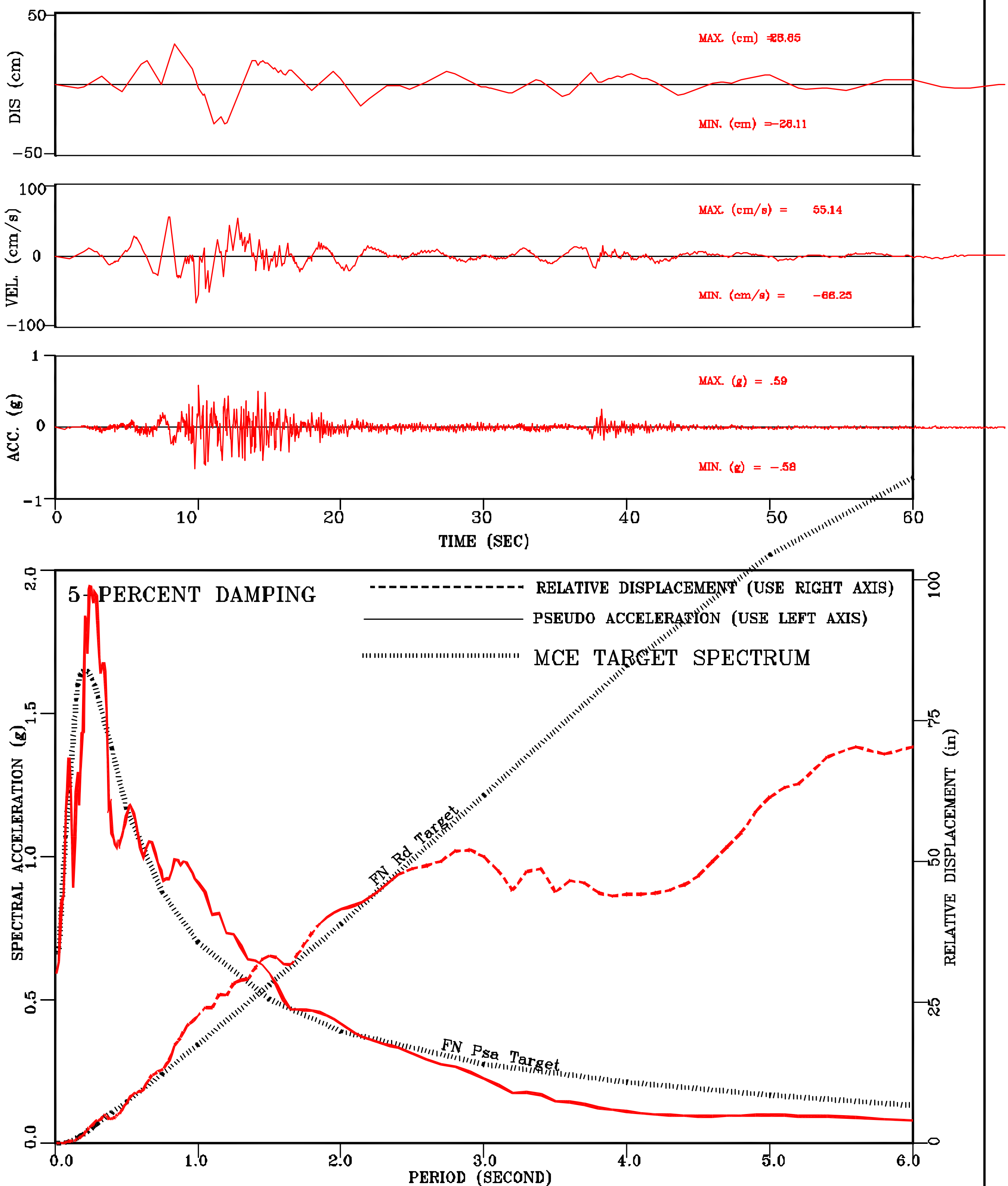
DEVIL'S SLIDE TUNNELS

EMI Project No.: 01-119 | Date: 8/20/01

MCE SET-2B ROCK MOTION
Modified from 1999 Turkey ARC Record
Motions Matched to 45-Deg. Spectrum
135-Deg. Counter Clockwise from FN

Figure 23



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Geotechnical and Earthquake Engineering

DEVIL'S SLIDE TUNNELS

EMI Project No.: 01-119

Date: 8/20/01

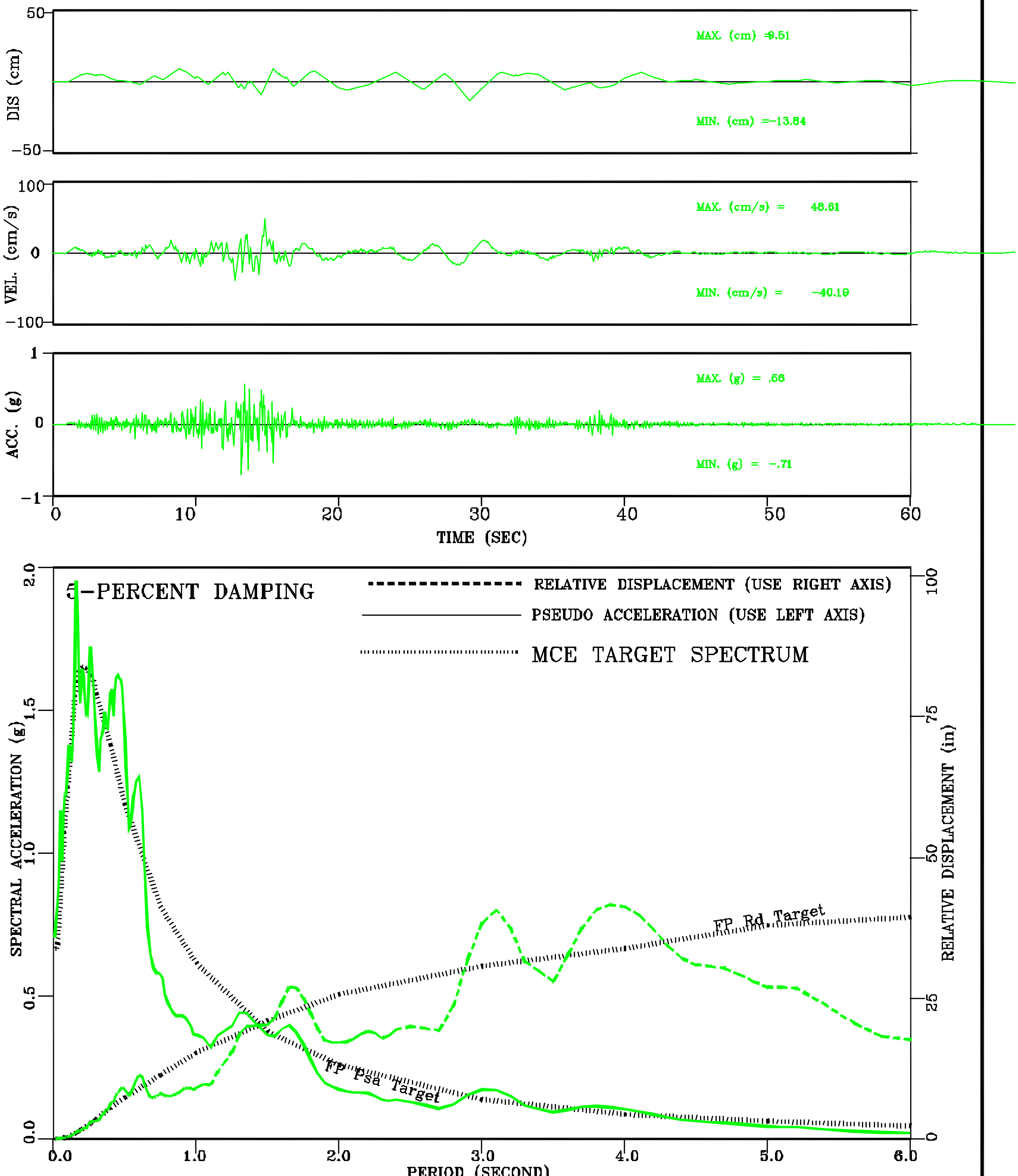
MCE SET-2B ROCK MOTION

Modified from 1999 Turkey ARC Record

Motions Matched to 45-Deg. Spectrum

FAULT NORMAL COMPONENT

Figure 24



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DEVIL'S SLIDE TUNNELS

EMI Project No.: 01-119 | Date:8/20/01

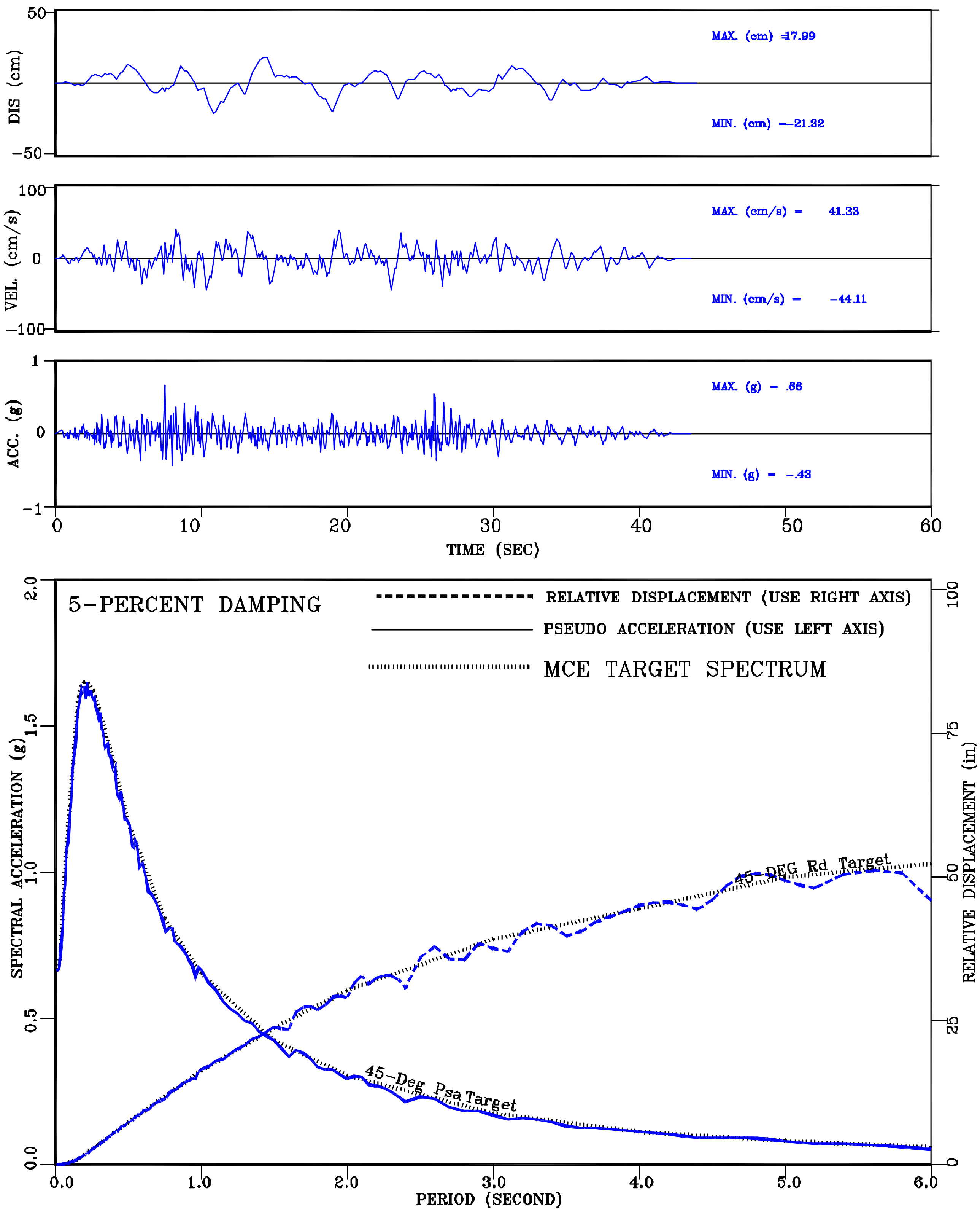
MCE SET-2B ROCK MOTION

Modified from 1999 Turkey ARC Record

Motions Matched to 45-Deg. Spectrum

FAULT PARALLEL COMPONENT

Figure 25



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DEVIL'S SLIDE TUNNELS

EMI Project No.: 01-119 | Date: 8/20/01

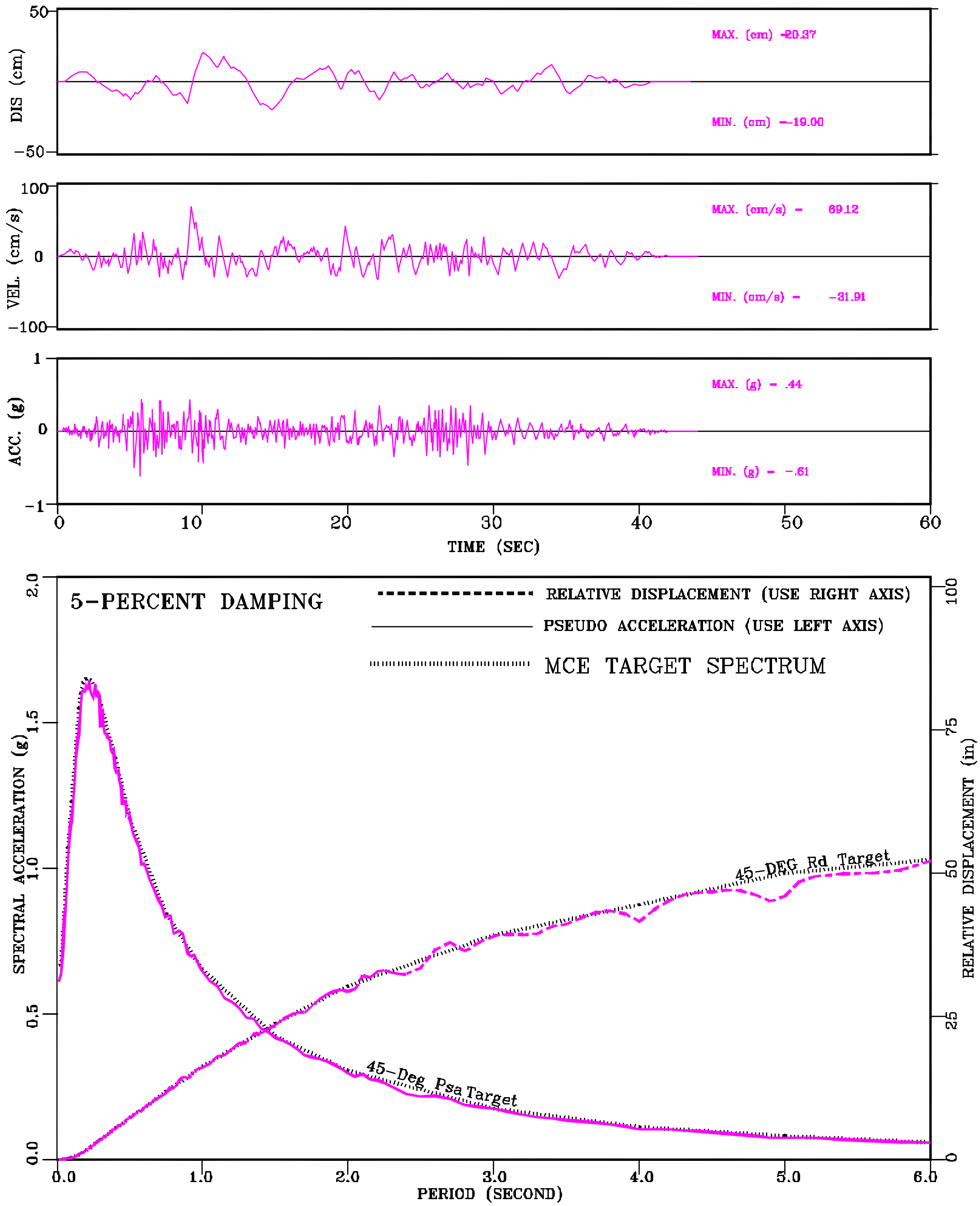
MCE SET-3B ROCK MOTION

MODIFIED FROM 1992 LANDERS YERMO RECORD

Motion Matched to 45-Deg. Spectrum

45-Deg. Counter Clockwise from FN

FIGURE 26



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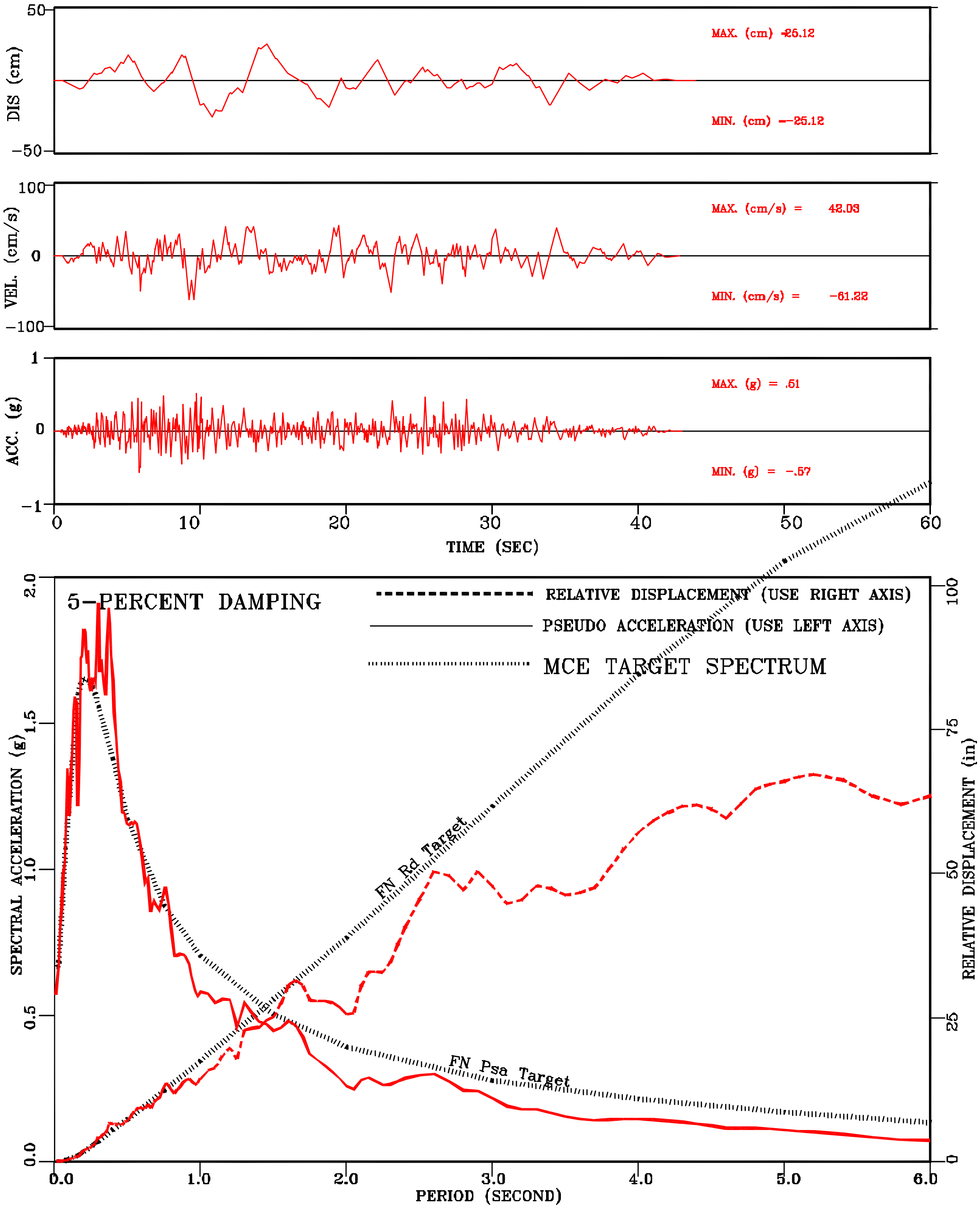
DEVIL'S SLIDE TUNNELS

EMI Project No.: 01-119 | Date:8/20/01

MCE SET-3B ROCK MOTION
MODIFIED FROM 1992 LANDERS YERMO RECORD
Motion Matched to 45-Deg. Spectrum
135-Deg. Counter Clockwise from FN

Figure 27



Earth Mechanics, Inc.

Geotechnical and Earthquake Engineering

DEVIL'S SLIDE TUNNELS

EMI Project No.: 01-119 | **Date:** 8/20/01

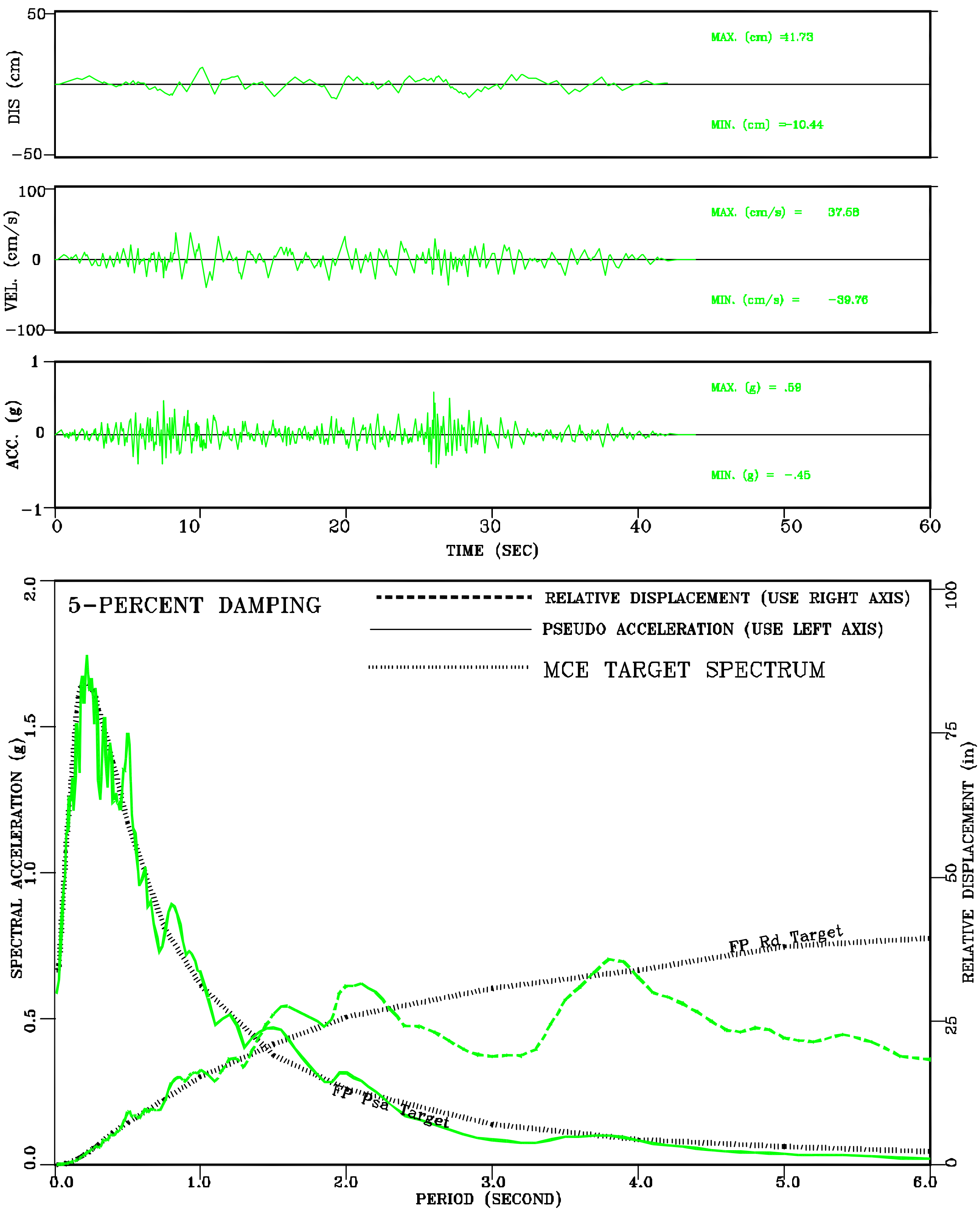
MCE SET-3B ROCK MOTION

MODIFIED FROM 1992 LANDERS YERMO RECORD

Motion Matched to 45-Deg. Spectrum

FAULT NORMAL COMPONENT

Figure 28



Earth Mechanics, Inc.

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DEVIL'S SLIDE TUNNELS

EMI Project No.: 01-119 | Date:8/20/01

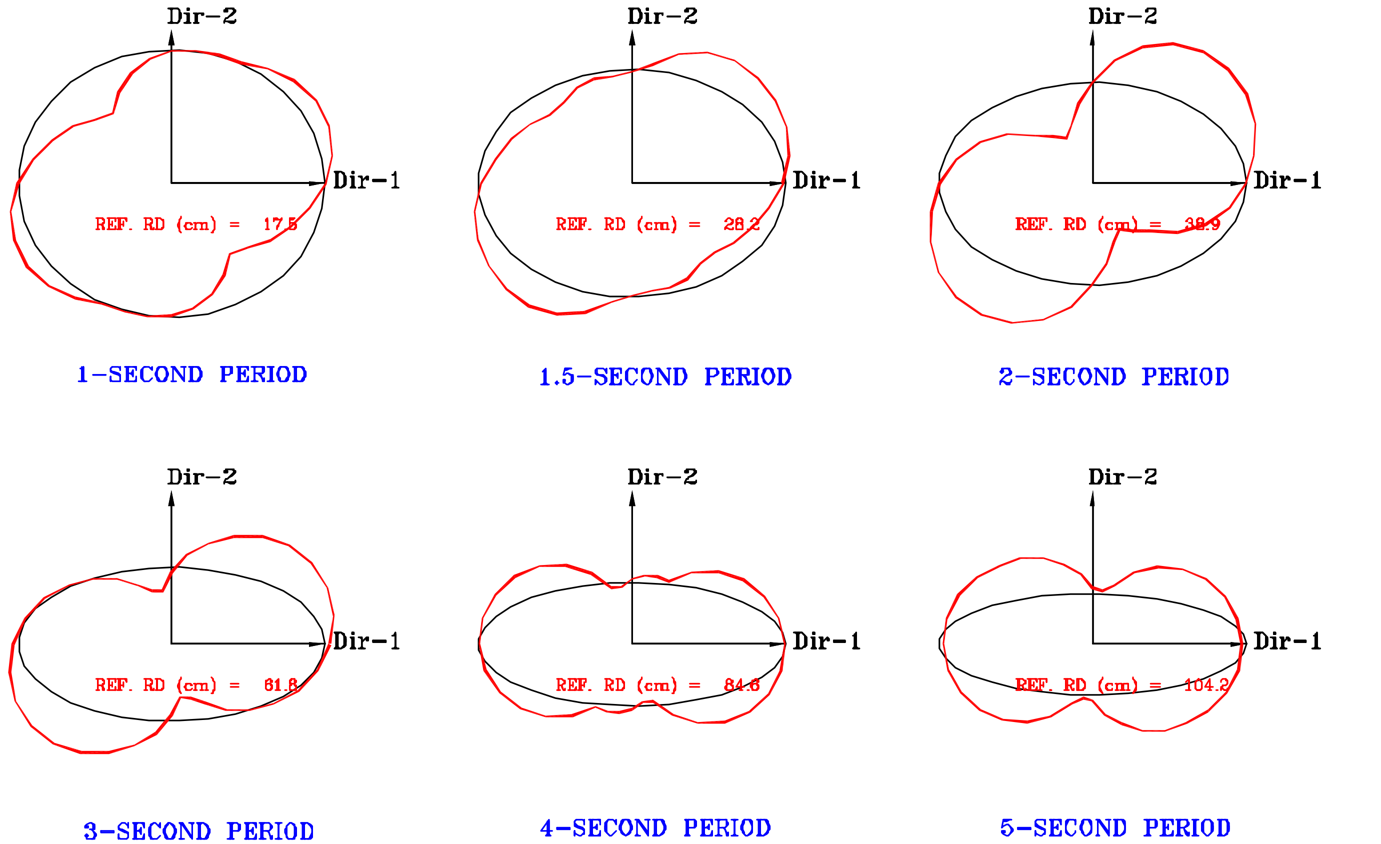
MCE SET-3B ROCK MOTION

MODIFIED FROM 1992 LANDERS YERMO RECORD

Motion Matched to 45-Deg. Spectrum

FAULT PARALLEL COMPONENT

Figure 29

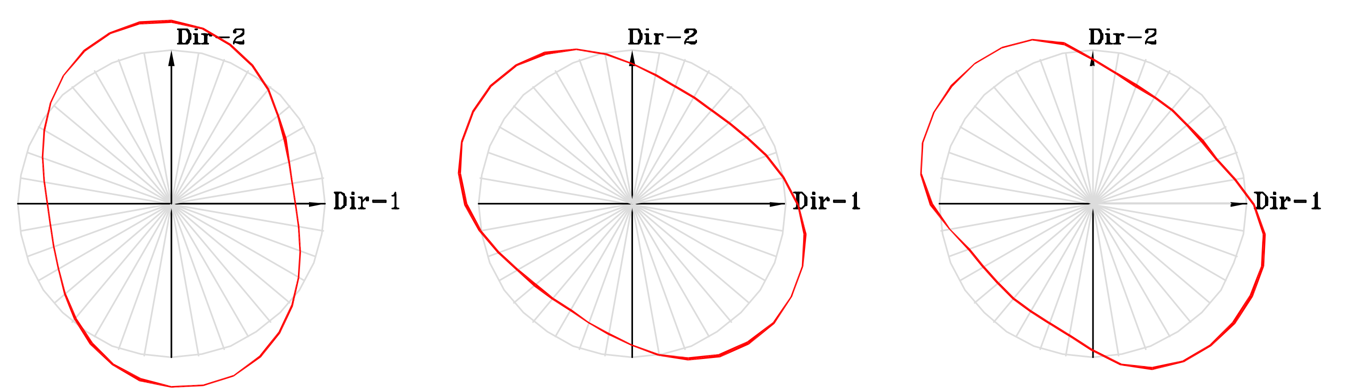


SHAKING INTENSITY AT VARIOUS AZIMUTHS

at Dir–1 = FAULT NORMAL COMPONENT
at Dir–2 = FAULT PARALLEL COMPONENT

CROSS–CORRELATION STATISTICS FOR Dir–1 and Dir–2

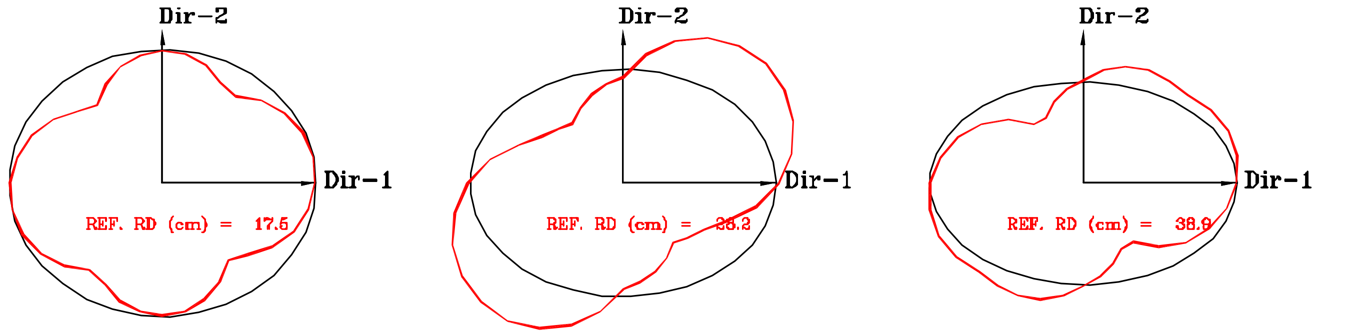
ACCELERATION	VELOCITY	DISPLACEMENT
CROSS CORREL. COEFF. = –.11	CROSS CORREL. COEFF. = .20	CROSS CORREL. COEFF. = .20
PRINC. DIR. AT (DEG) = –36.3	PRINC. DIR. AT (DEG) = 10.6	PRINC. DIR. AT (DEG) = 4.6
MAX. COEFFICIENT = .116	MAX. COEFFICIENT = .486	MAX. COEFFICIENT = .790
AT DIRECTION (DEG)= 100.0	AT DIRECTION (DEG)= 150.0	AT DIRECTION (DEG)= 320.0



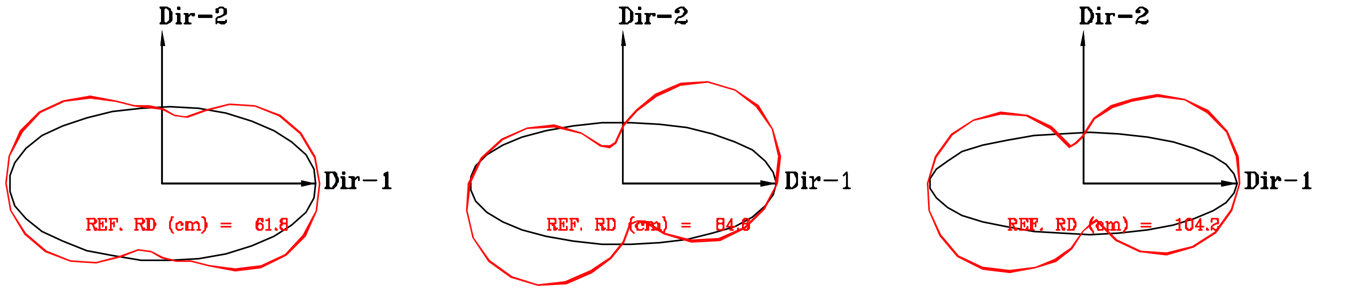
ACCELERATION VELOCITY DISPLACEMENT

CROSS CORRELATION COEFFICIENT OF RECORDS UNDER ROTATION

Earth Mechanics, Inc.	DEVIL'S SLIDE TUNNELS	SHAKING AND CROSS–CORRELATION VS. ROTATION, SET–1A MOTION
	PROJECT NO. 01–119	8/20/01	FIGURE 30



1-SECOND PERIOD　　1.5-SECOND PERIOD　　2-SECOND PERIOD



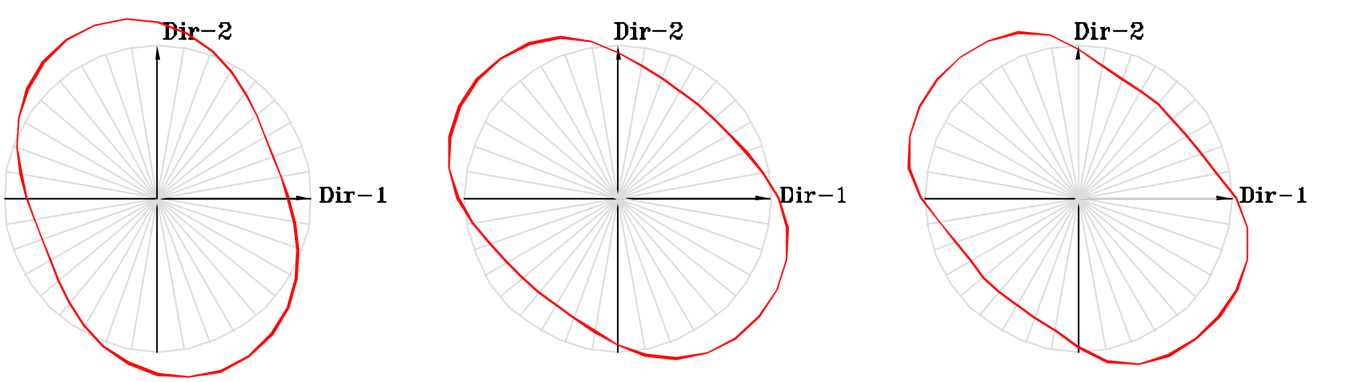
3-SECOND PERIOD　　4-SECOND PERIOD　　5-SECOND PERIOD

SHAKING INTENSITY AT VARIOUS AZIMUTHS

at Dir-1 = FAULT NORMAL COMPONENT
at Dir-2 = FAULT PARALLEL COMPONENT

CROSS-CORRELATION STATISTICS FOR Dir-1 and Dir-2

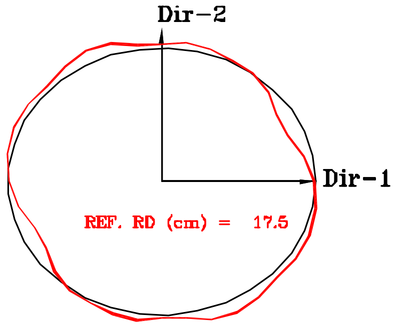
ACCELERATION	VELOCITY	DISPLACEMENT
CROSS CORREL. COEFF. = -.12	CROSS CORREL. COEFF. = .14	CROSS CORREL. COEFF. = .10
PRINC. DIR. AT (DEG) = -23.8	PRINC. DIR. AT (DEG) = 5.4	PRINC. DIR. AT (DEG) = 2.3
MAX. COEFFICIENT = .156	MAX. COEFFICIENT = .598	MAX. COEFFICIENT = .793
AT DIRECTION (DEG)= 290.0	AT DIRECTION (DEG)= 140.0	AT DIRECTION (DEG)= 140.0



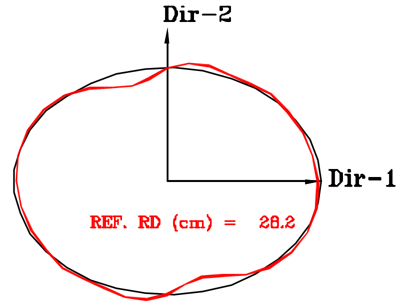
ACCELERATION　　VELOCITY　　DISPLACEMENT

CROSS CORRELATION COEFFICIENT OF RECORDS UNDER ROTATION

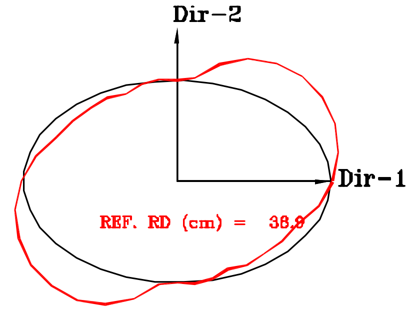
Earth Mechanics, Inc.	DEVIL'S SLIDE TUNNELS		SHAKING AND CROSS-CORRELATION VS. ROTATION SET-2A MOTION FIGURE 31
	PROJECT NO. 01-119	8/20/01	



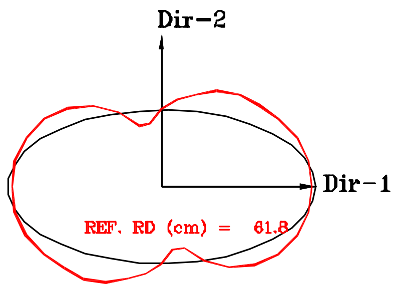
1-SECOND PERIOD



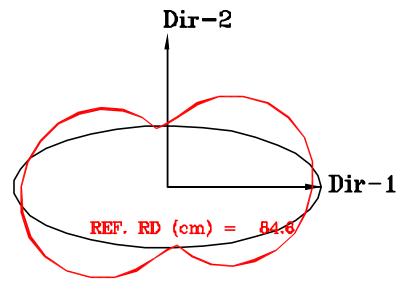
1.5-SECOND PERIOD



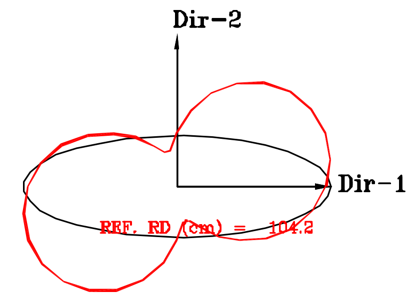
2-SECOND PERIOD



3-SECOND PERIOD



4-SECOND PERIOD



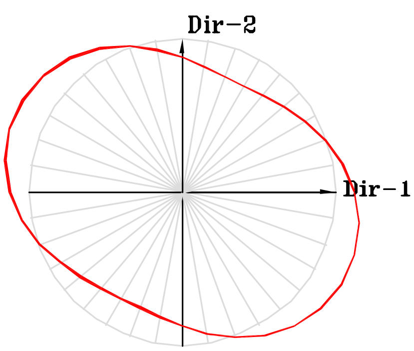
5-SECOND PERIOD

SHAKING INTENSITY AT VARIOUS AZIMUTHS

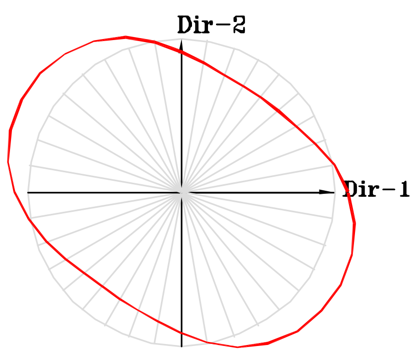
at Dir-1 = FAULT NORMAL COMPONENT
at Dir-2 = FAULT PARALLEL COMPONENT

CROSS-CORRELATION STATISTICS FOR Dir-1 and Dir-2

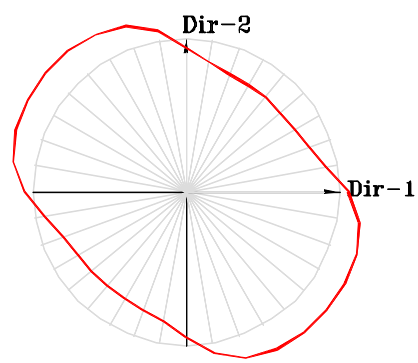
ACCELERATION	VELOCITY	DISPLACEMENT
CROSS CORREL. COEFF. = .10	CROSS CORREL. COEFF. = .23	CROSS CORREL. COEFF. = .24
PRINC. DIR. AT (DEG) = 18.7	PRINC. DIR. AT (DEG) = 11.1	PRINC. DIR. AT (DEG) = 4.5
MAX. COEFFICIENT = .164	MAX. COEFFICIENT = .522	MAX. COEFFICIENT = .844
AT DIRECTION (DEG)= 150.0	AT DIRECTION (DEG)= 150.0	AT DIRECTION (DEG)= 140.0



ACCELERATION



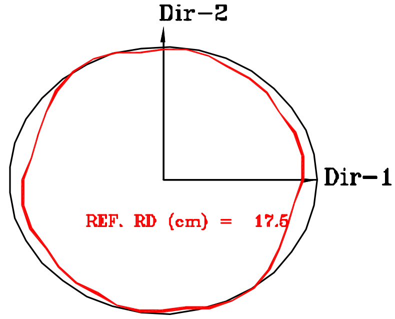
VELOCITY



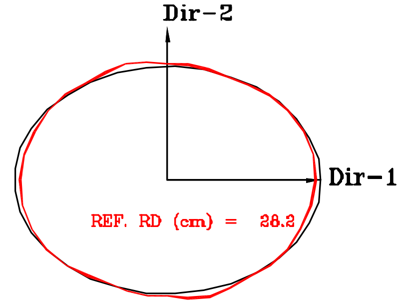
DISPLACEMENT

CROSS CORRELATION COEFFICIENT OF RECORDS UNDER ROTATION

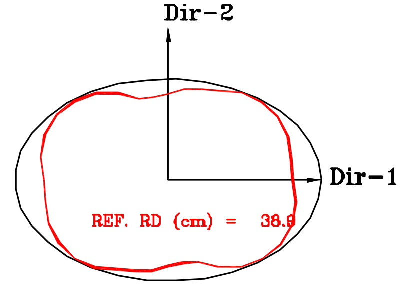
Earth Mechanics, Inc.	DEVIL'S SLIDE TUNNELS		SHAKING AND CROSS-CORRELATION VS. ROTATION
	PROJECT NO. 01-119	8/20/01	SET-3A MOTION
			FIGURE 32



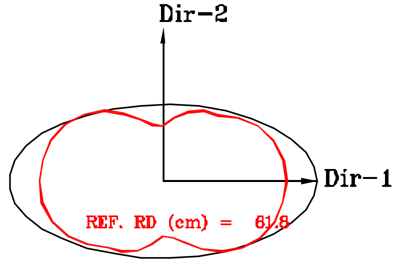
1-SECOND PERIOD



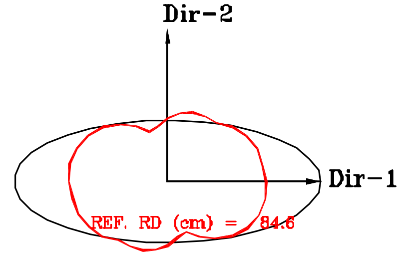
1.5-SECOND PERIOD



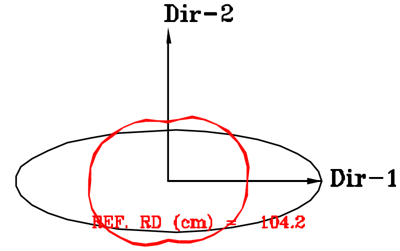
2-SECOND PERIOD



3-SECOND PERIOD



4-SECOND PERIOD



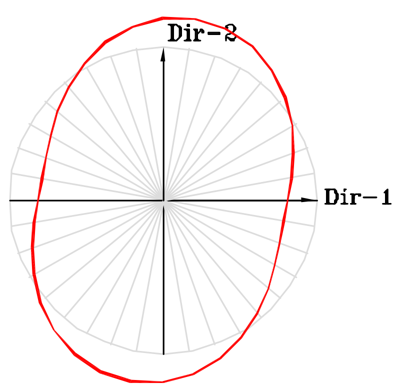
5-SECOND PERIOD

SHAKING INTENSITY AT VARIOUS AZIMUTHS

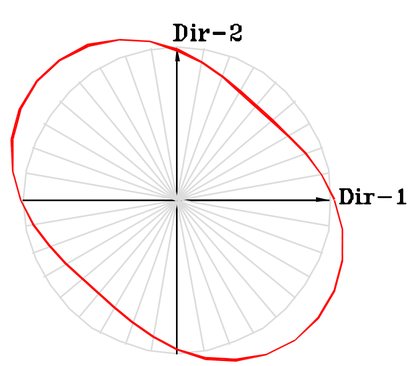
at Dir-1 = FAULT NORMAL COMPONENT
at Dir-2 = FAULT PARALLEL COMPONENT

CROSS-CORRELATION STATISTICS FOR Dir-1 and Dir-2

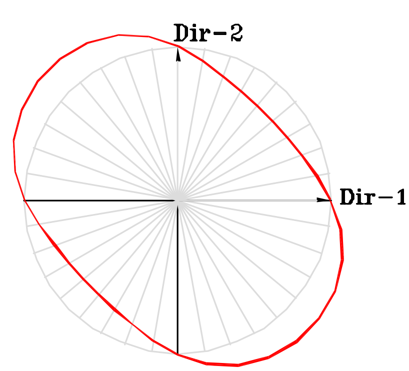
ACCELERATION	VELOCITY	DISPLACEMENT
CROSS CORREL. COEFF. = -.09	CROSS CORREL. COEFF. = .02	CROSS CORREL. COEFF. = -.01
PRINC. DIR. AT (DEG) = -34.2	PRINC. DIR. AT (DEG) = 3.1	PRINC. DIR. AT (DEG) = -.6
MAX. COEFFICIENT = .095	MAX. COEFFICIENT = .203	MAX. COEFFICIENT = .507
AT DIRECTION (DEG)= 80.0	AT DIRECTION (DEG)= 140.0	AT DIRECTION (DEG)= 310.0



ACCELERATION



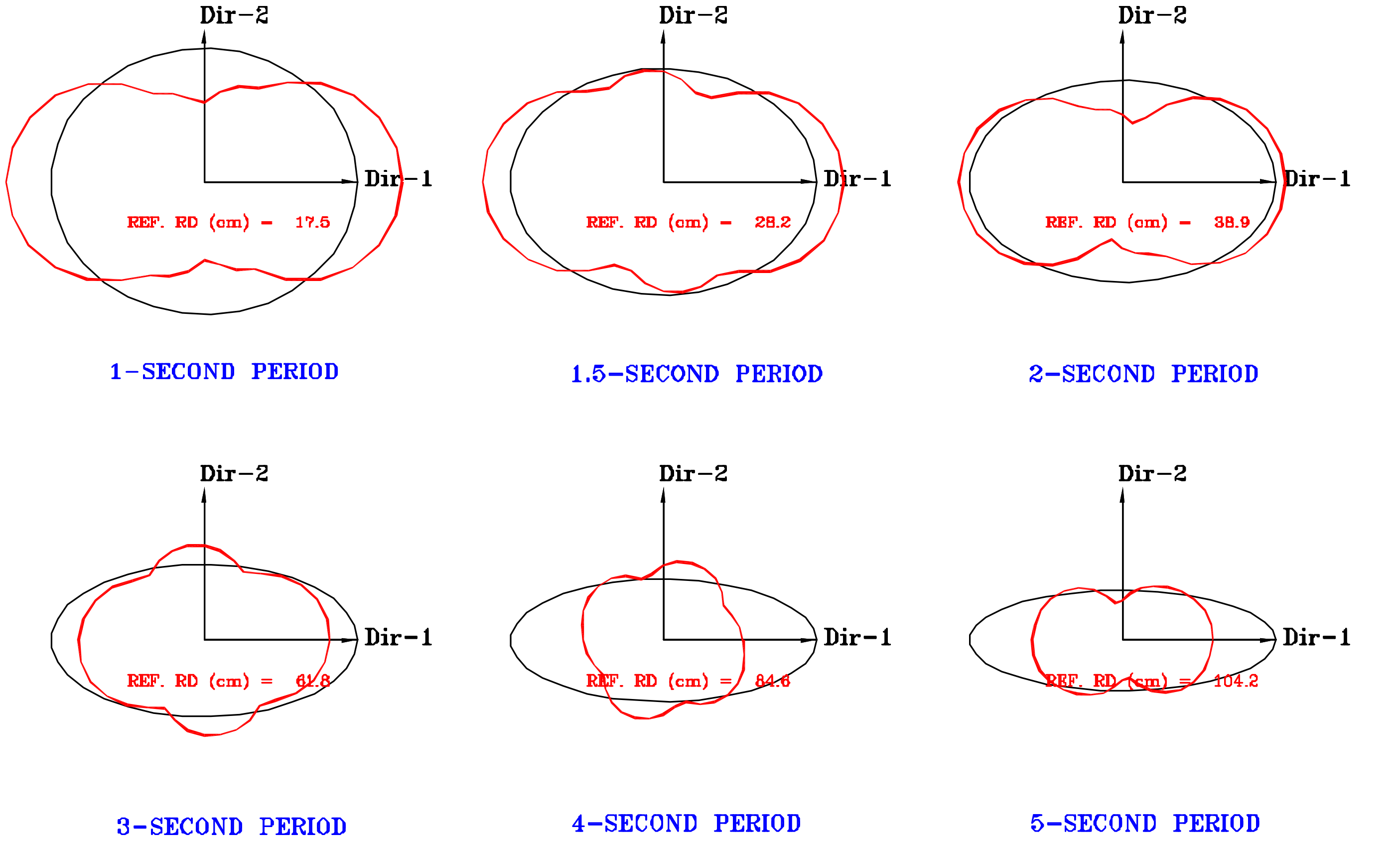
VELOCITY



DISPLACEMENT

CROSS CORRELATION COEFFICIENT OF RECORDS UNDER ROTATION

Earth Mechanics, Inc.	DEVIL'S SLIDE TUNNELS		SHAKING AND CROSS-CORRELATION VS. ROTATION SET-1B MOTION
	PROJECT NO. 01-119	8/20/01	FIGURE 33

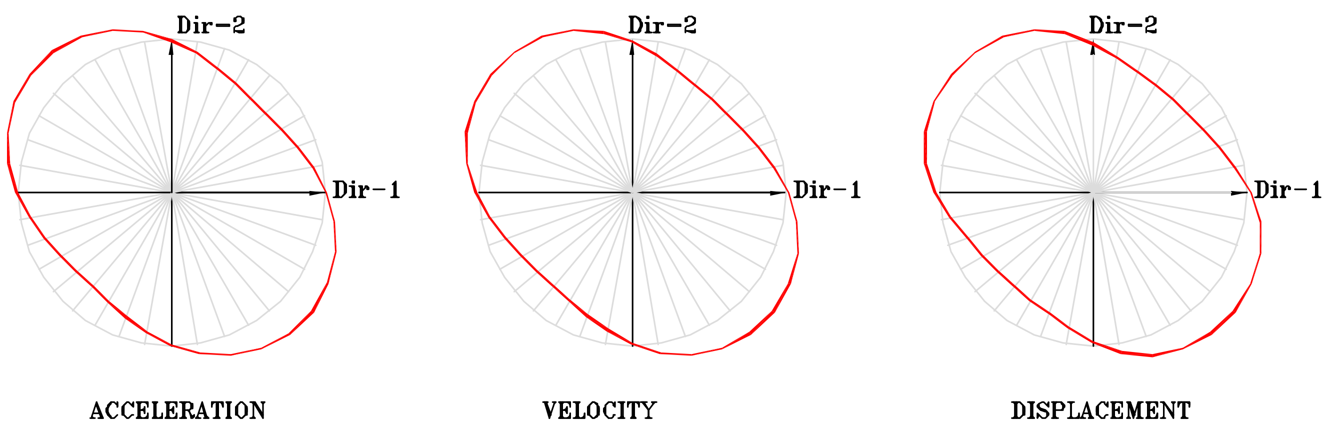


SHAKING INTENSITY AT VARIOUS AZIMUTHS

at Dir-1 = FAULT NORMAL COMPONENT
at Dir-2 = FAULT PARALLEL COMPONENT

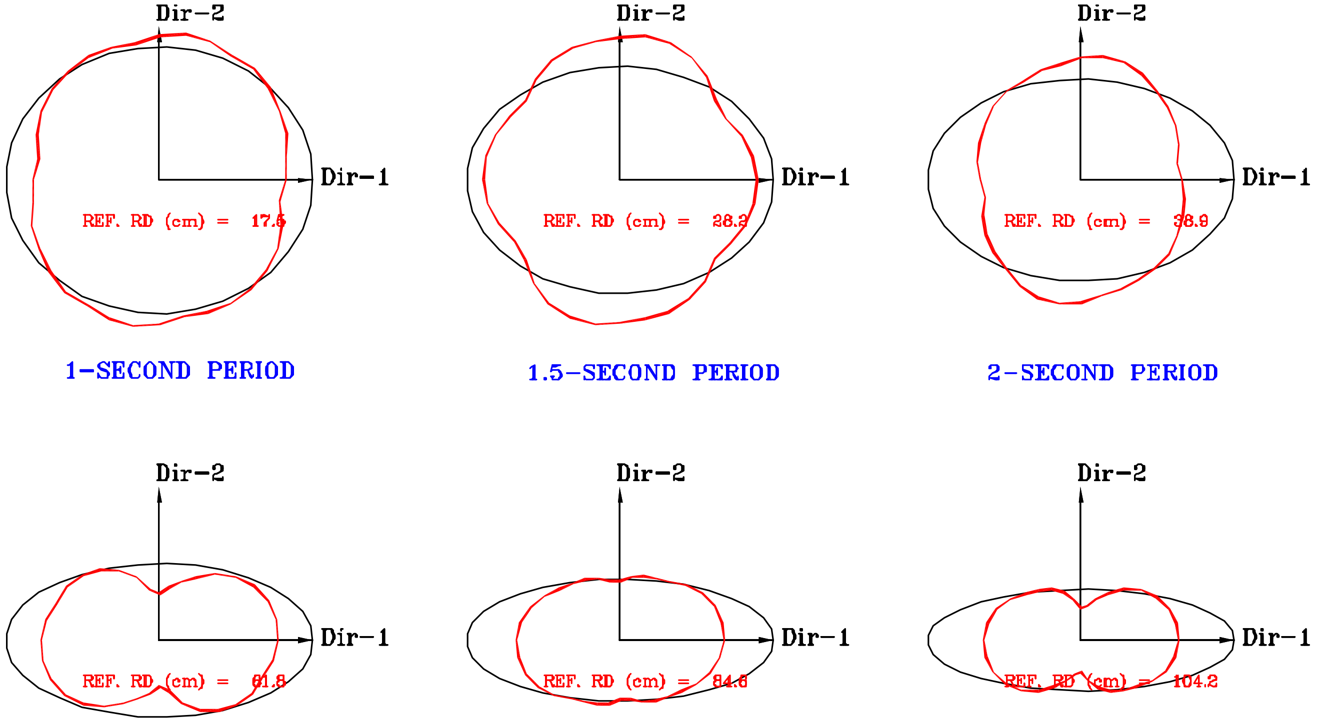
CROSS-CORRELATION STATISTICS FOR Dir-1 and Dir-2

ACCELERATION	VELOCITY	DISPLACEMENT
CROSS CORREL. COEFF. = .01	CROSS CORREL. COEFF. = .04	CROSS CORREL. COEFF. = .09
PRINC. DIR. AT (DEG) = 1.0	PRINC. DIR. AT (DEG) = 2.1	PRINC. DIR. AT (DEG) = 3.2
MAX. COEFFICIENT = .140	MAX. COEFFICIENT = .435	MAX. COEFFICIENT = .610
AT DIRECTION (DEG)= 140.0	AT DIRECTION (DEG)= 140.0	AT DIRECTION (DEG)= 320.0



CROSS CORRELATION COEFFICIENT OF RECORDS UNDER ROTATION

Earth Mechanics, Inc.	DEVIL'S SLIDE TUNNELS	SHAKING AND CROSS-CORRELATION VS. ROTATION SET-2B MOTION
	PROJECT NO. 01-119 | 8/20/01	FIGURE 34



1-SECOND PERIOD | 1.5-SECOND PERIOD | 2-SECOND PERIOD

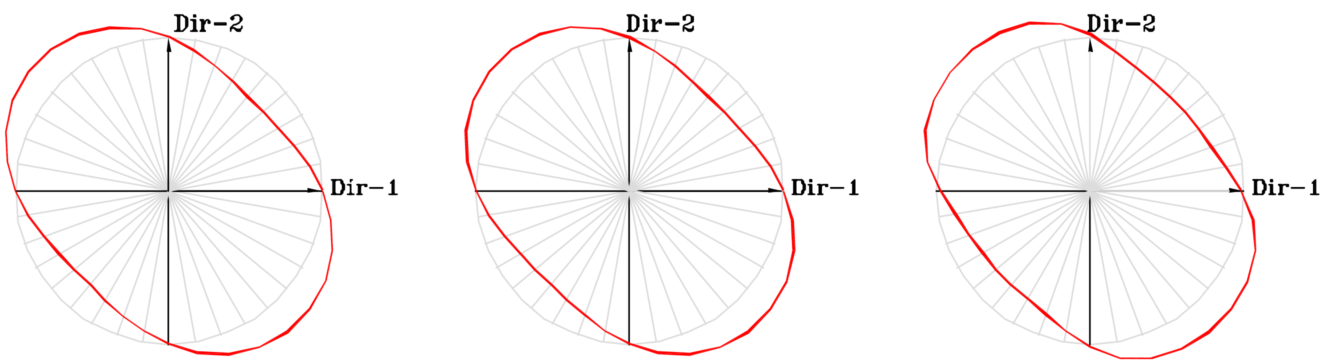
3-SECOND PERIOD | 4-SECOND PERIOD | 5-SECOND PERIOD

SHAKING INTENSITY AT VARIOUS AZIMUTHS

at Dir-1 = FAULT NORMAL COMPONENT
at Dir-2 = FAULT PARALLEL COMPONENT

CROSS-CORRELATION STATISTICS FOR Dir-1 and Dir-2

	ACCELERATION	VELOCITY	DISPLACEMENT
CROSS CORREL. COEFF. =	.00	.00	-.07
PRINC. DIR. AT (DEG) =	-.1	.2	-1.9
MAX. COEFFICIENT =	.139	.310	.704
AT DIRECTION (DEG)=	310.0	140.0	310.0



ACCELERATION | VELOCITY | DISPLACEMENT

CROSS CORRELATION COEFFICIENT OF RECORDS UNDER ROTATION

Earth Mechanics, Inc.

DEVIL'S SLIDE TUNNELS

PROJECT NO. 01-119 | 8/20/01

SHAKING AND CROSS-CORRELATION VS. ROTATION
SET-3B MOTION

FIGURE 35

APPENDIX A
DETAILS OF PROBABILISTIC AND DETERMINISTIC SEISMIC HAZARD ANALYSES PRESENTED DURING JUNE 20 MEETING

June 18, 2001

To: Gordon Marsh
From: Norm Abrahamson

Subject: Ground Motions for Devil Slide Tunnel

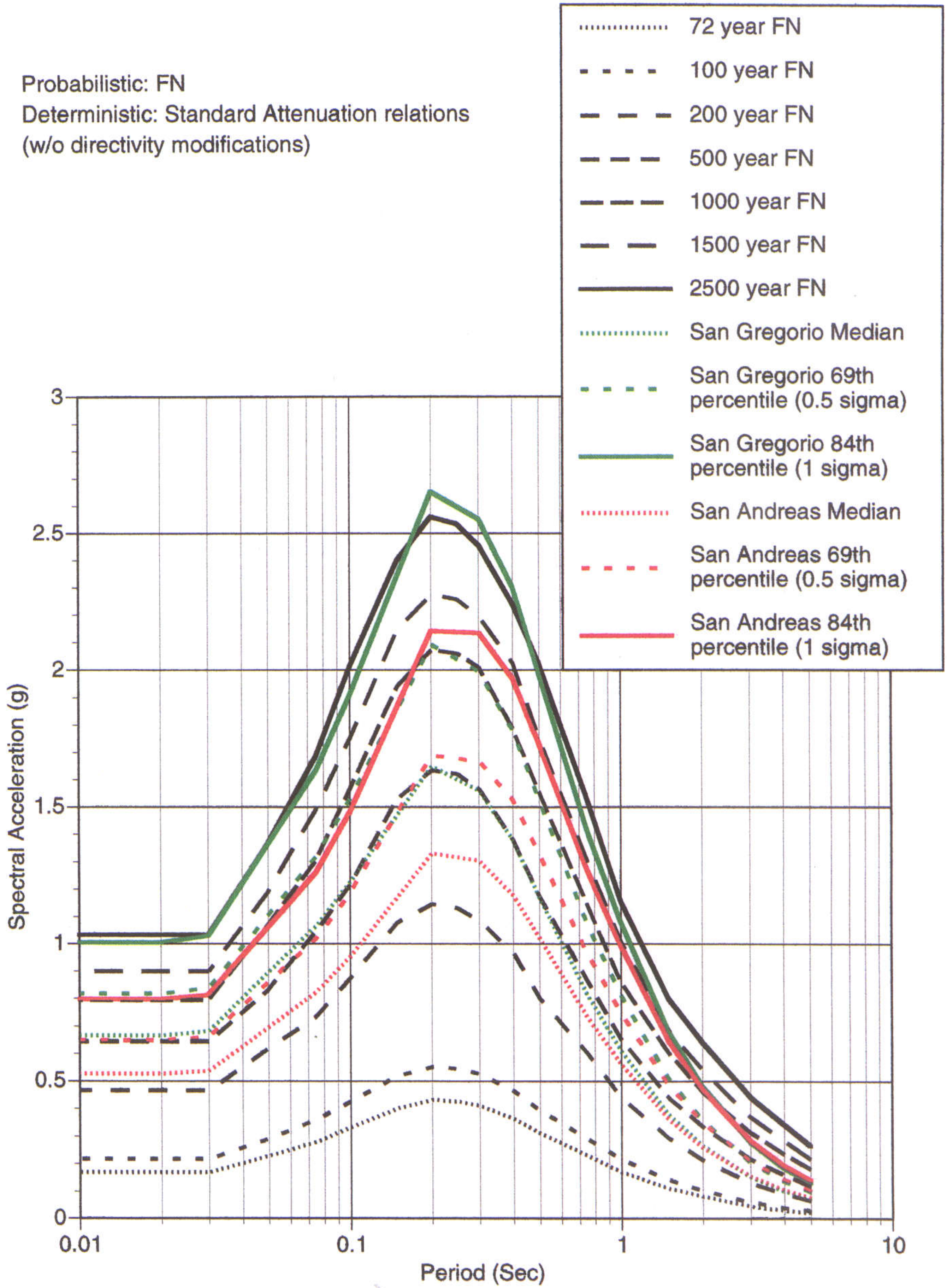
The attached plots compare the response spectra from deterministic and probabilistic approaches. For the deterministic approach, the following parameters were used for the MCE for the San Andreas and San Gregorios faults:

Fault	Magnitude	Distance
San Andreas	8.0	8 km
San Gregorio	7.5	3 km

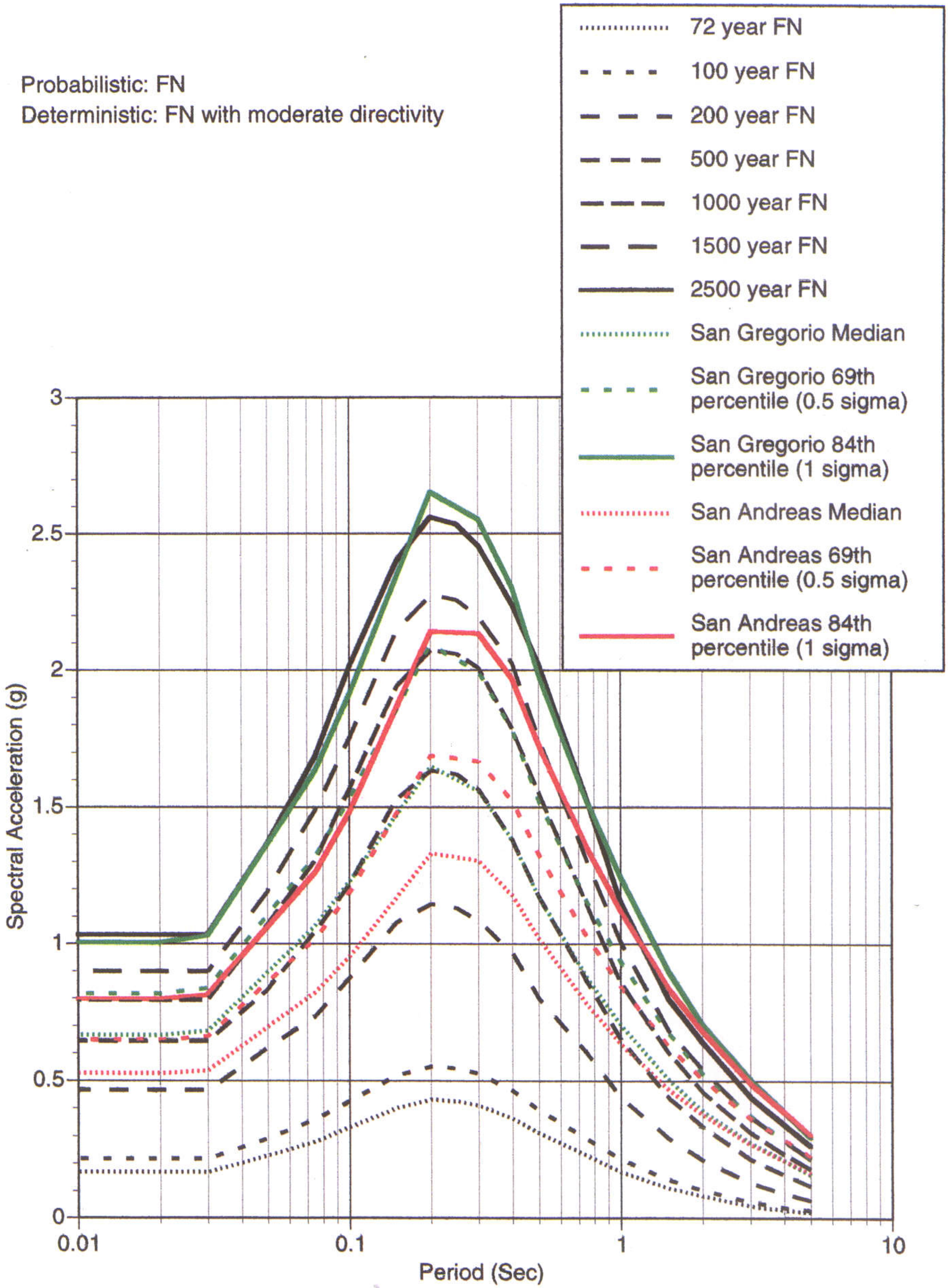
For each MCE, the ground motion was computed using three different deterministic probability levels and three different directivity conditions for a total of 9 combinations. The three probability levels are median (0 sigma), 69^{th} percentile (0.5 sigma), and 84^{th} percentile (1.0 sigma). The three directivity conditions are : no modification, full directivity, and moderate directivity.

The 5% damped response spectra are shown separately for each directivity condition to keep the number of curves on a plot manageable. The three directivity conditions for the fault normal component are shown in Figures 1,2 and 3. The three directivity conditions for the fault parallel component are shown in Figures 4, 5, and 6.

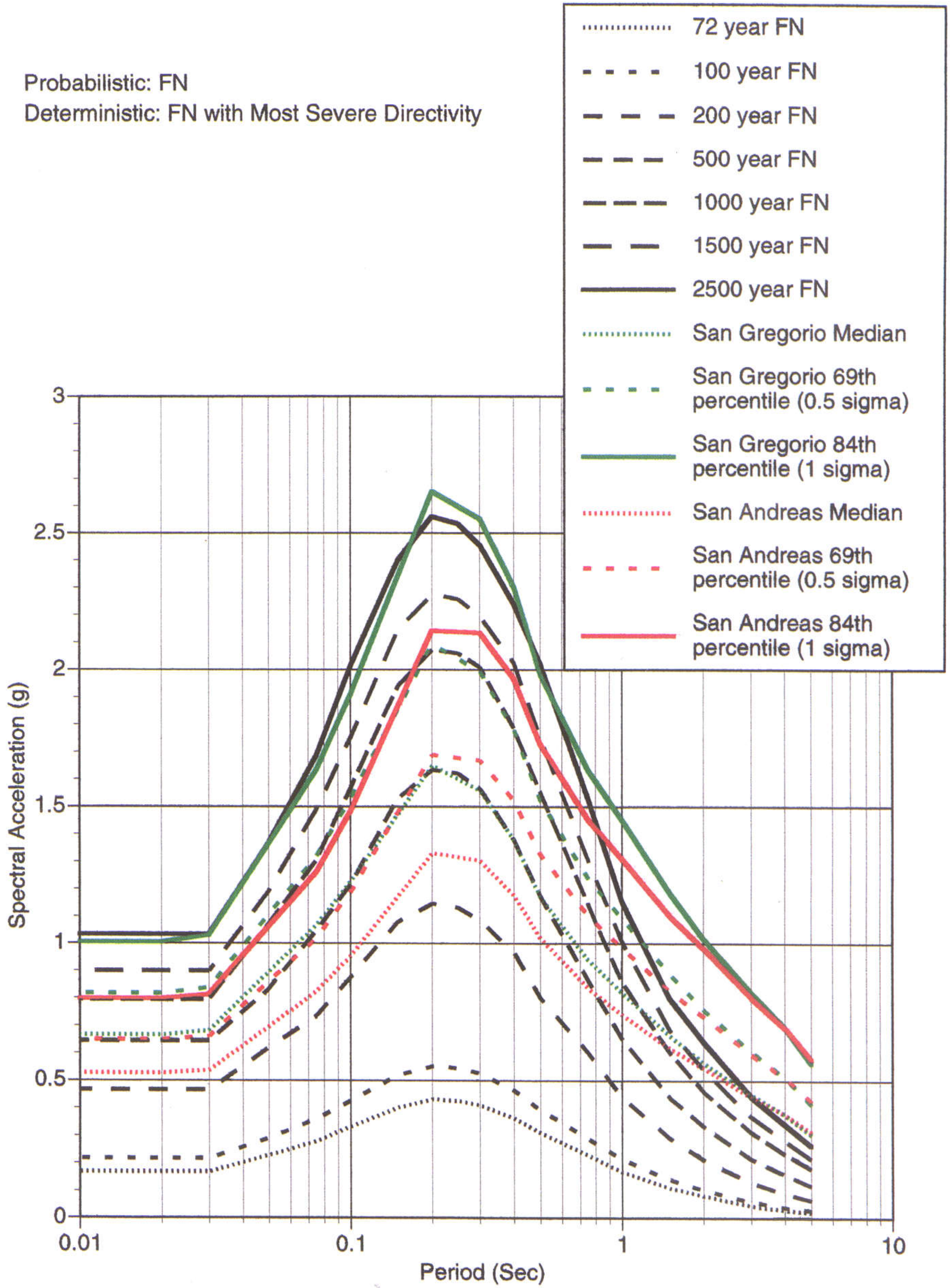
The vertical component is computed using the V/H ratio appropriate for the selected horizontal spectrum. The plots of the vertical component are nor included in this section.



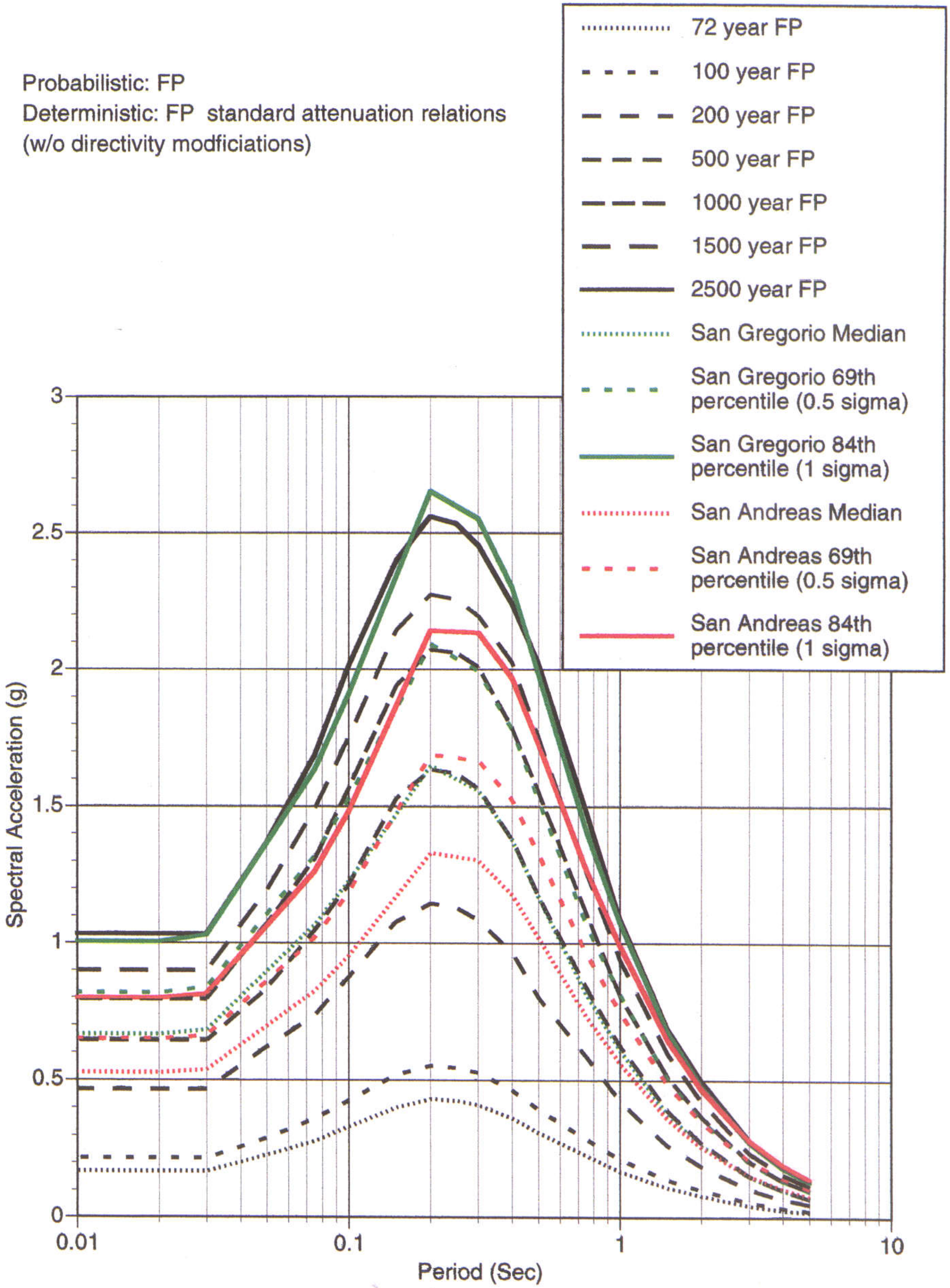
Probabilistic: FN
Deterministic: Standard Attenuation relations
(w/o directivity modifications)
72 year FN
100 year FN
200 year FN
500 year FN
1000 year FN
1500 year FN
2500 year FN
San Gregorio Median
San Gregorio 69th percentile (0.5 sigma)
San Gregorio 84th percentile (1 sigma)
San Andreas Median
San Andreas 69th percentile (0.5 sigma)
San Andreas 84th percentile (1 sigma)
Spectral Acceleration (g)
0
0.5
1
1.5
2
2.5
3
0.01
0.1
1
10
Period (Sec)



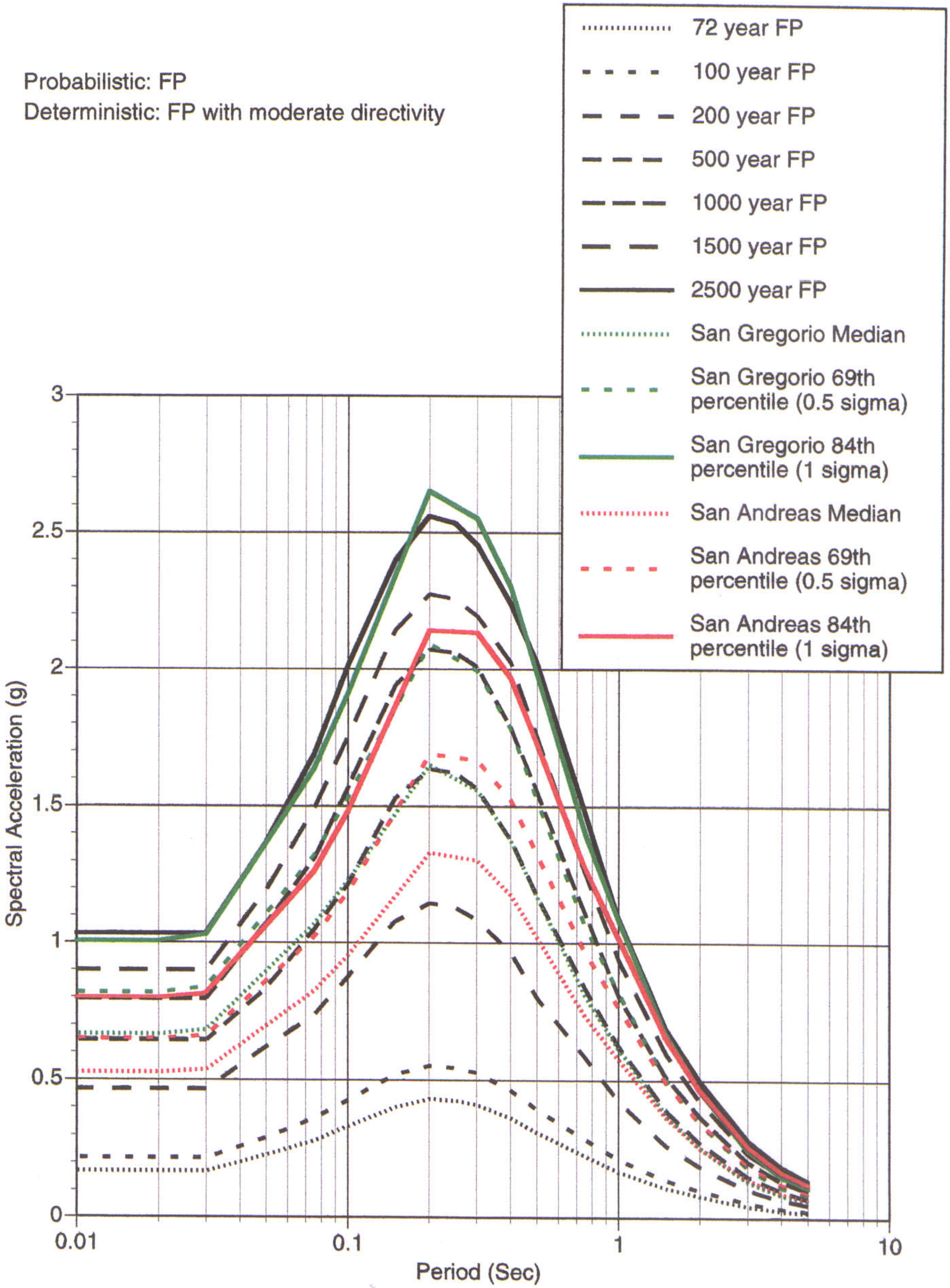
Probabilistic: FN
Deterministic: FN with moderate directivity
72 year FN
100 year FN
200 year FN
500 year FN
1000 year FN
1500 year FN
2500 year FN
San Gregorio Median
San Gregorio 69th percentile (0.5 sigma)
San Gregorio 84th percentile (1 sigma)
San Andreas Median
San Andreas 69th percentile (0.5 sigma)
San Andreas 84th percentile (1 sigma)
Spectral Acceleration (g)
0
0.5
1
1.5
2
2.5
3
0.01
0.1
1
10
Period (Sec)



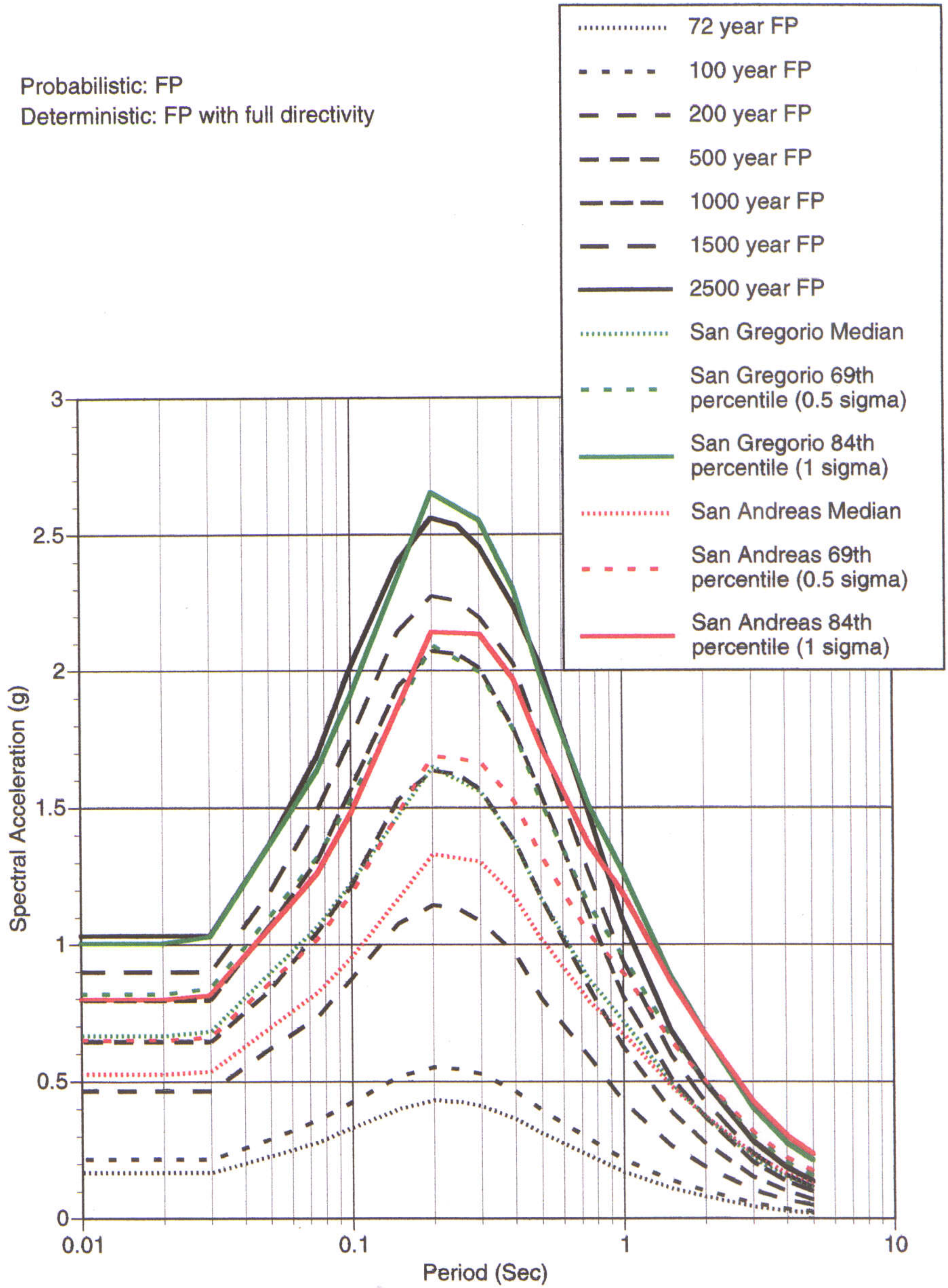
Probabilistic: FN
Deterministic: FN with Most Severe Directivity
72 year FN
100 year FN
200 year FN
500 year FN
1000 year FN
1500 year FN
2500 year FN
San Gregorio Median
San Gregorio 69th percentile (0.5 sigma)
San Gregorio 84th percentile (1 sigma)
San Andreas Median
San Andreas 69th percentile (0.5 sigma)
San Andreas 84th percentile (1 sigma)
Spectral Acceleration (g)
0
0.5
1
1.5
2
2.5
3
0.01
0.1
1
10
Period (Sec)



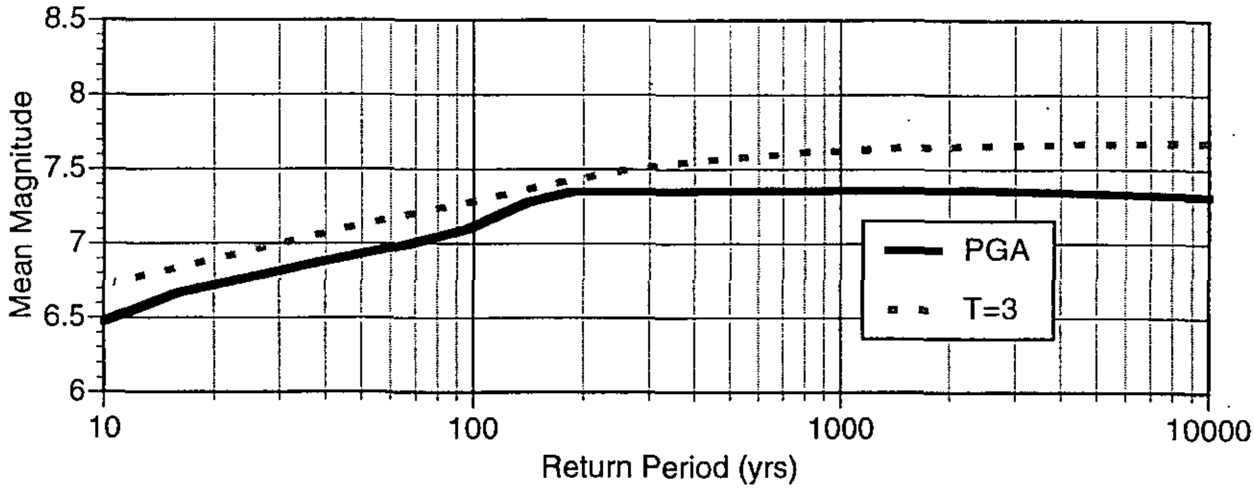
Probabilistic: FP
Deterministic: FP standard attenuation relations
(w/o directivity modficiations)
72 year FP
100 year FP
200 year FP
500 year FP
1000 year FP
1500 year FP
2500 year FP
San Gregorio Median
San Gregorio 69th percentile (0.5 sigma)
San Gregorio 84th percentile (1 sigma)
San Andreas Median
San Andreas 69th percentile (0.5 sigma)
San Andreas 84th percentile (1 sigma)
Spectral Acceleration (g)
3
2.5
2
1.5
1
0.5
0
0.01
0.1
1
10
Period (Sec)



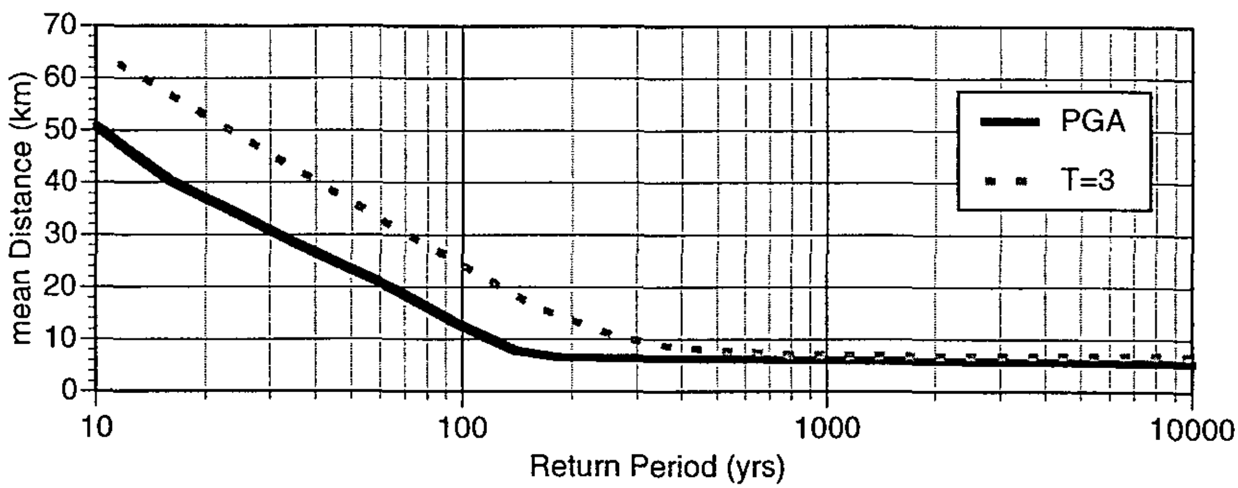
Probabilistic: FP
Deterministic: FP with moderate directivity
72 year FP
100 year FP
200 year FP
500 year FP
1000 year FP
1500 year FP
2500 year FP
San Gregorio Median
San Gregorio 69th percentile (0.5 sigma)
San Gregorio 84th percentile (1 sigma)
San Andreas Median
San Andreas 69th percentile (0.5 sigma)
San Andreas 84th percentile (1 sigma)
Spectral Acceleration (g)
0
0.5
1
1.5
2
2.5
3
0.01
0.1
1
10
Period (Sec)



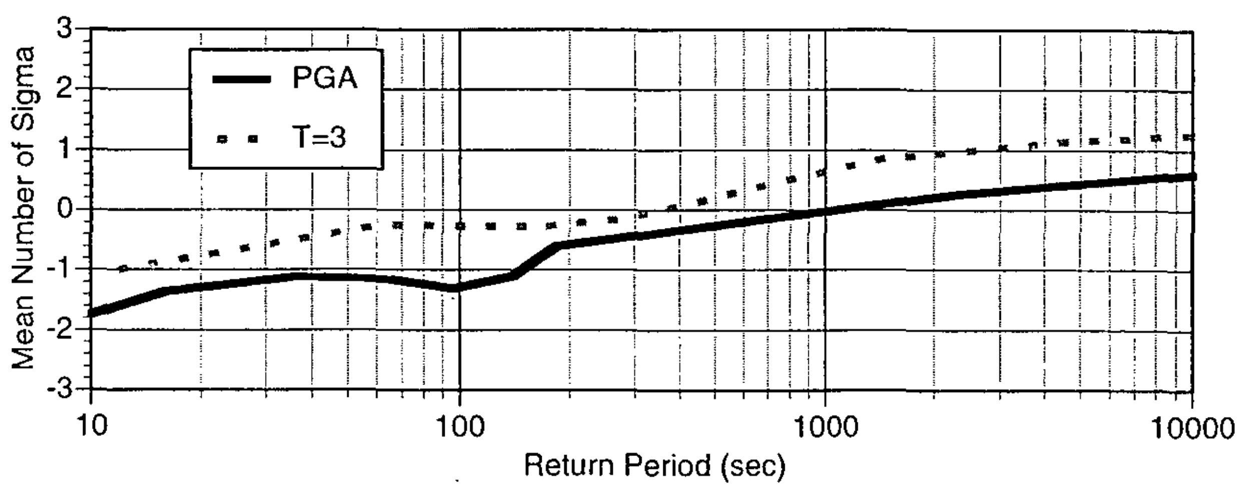
Probabilistic: FP
Deterministic: FP with full directivity
72 year FP
100 year FP
200 year FP
500 year FP
1000 year FP
1500 year FP
2500 year FP
San Gregorio Median
San Gregorio 69th percentile (0.5 sigma)
San Gregorio 84th percentile (1 sigma)
San Andreas Median
San Andreas 69th percentile (0.5 sigma)
San Andreas 84th percentile (1 sigma)
Spectral Acceleration (g)
0
0.5
1
1.5
2
2.5
3
0.01
0.1
1
10
Period (Sec)



8.5
8
7.5
7
6.5
6
Mean Magnitude
10
100
1000
10000
Return Period (yrs)
PGA
T=3

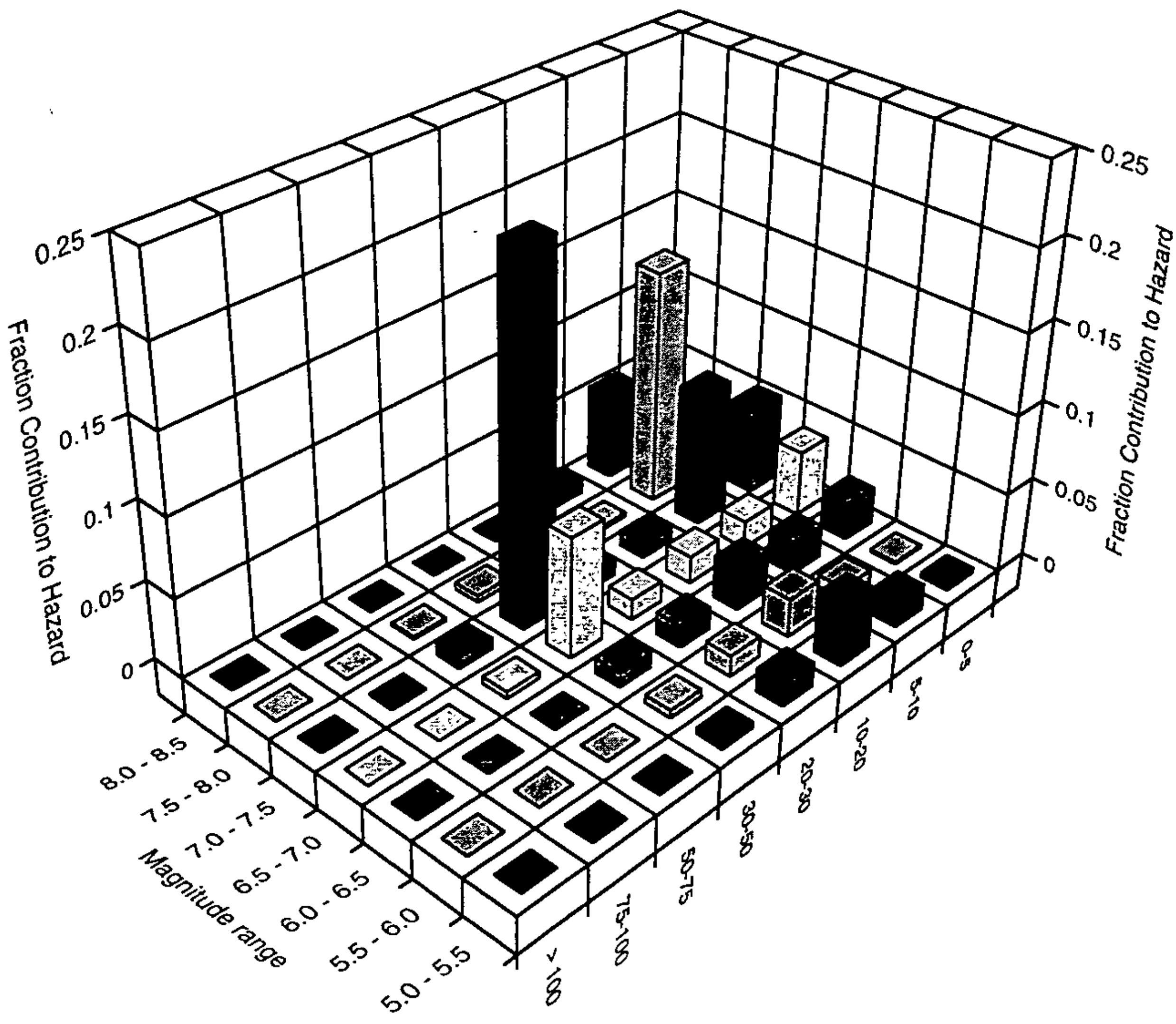


70
60
50
40
30
20
10
0
mean Distance (km)
10
100
1000
10000
Return Period (yrs)
PGA
T=3

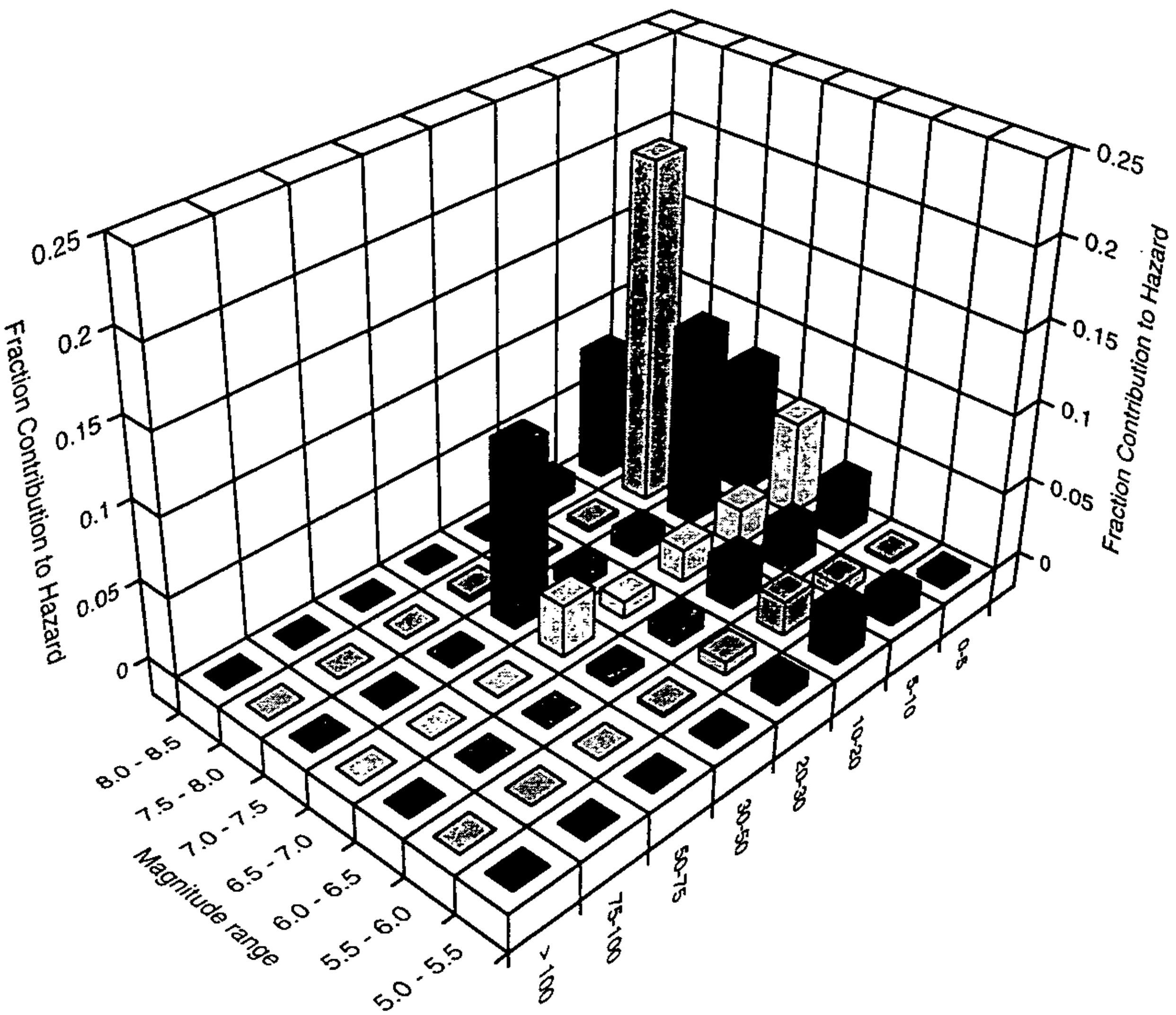


3
2
1
0
-1
-2
-3
Mean Number of Sigma
10
100
1000
10000
Return Period (sec)
PGA
T=3

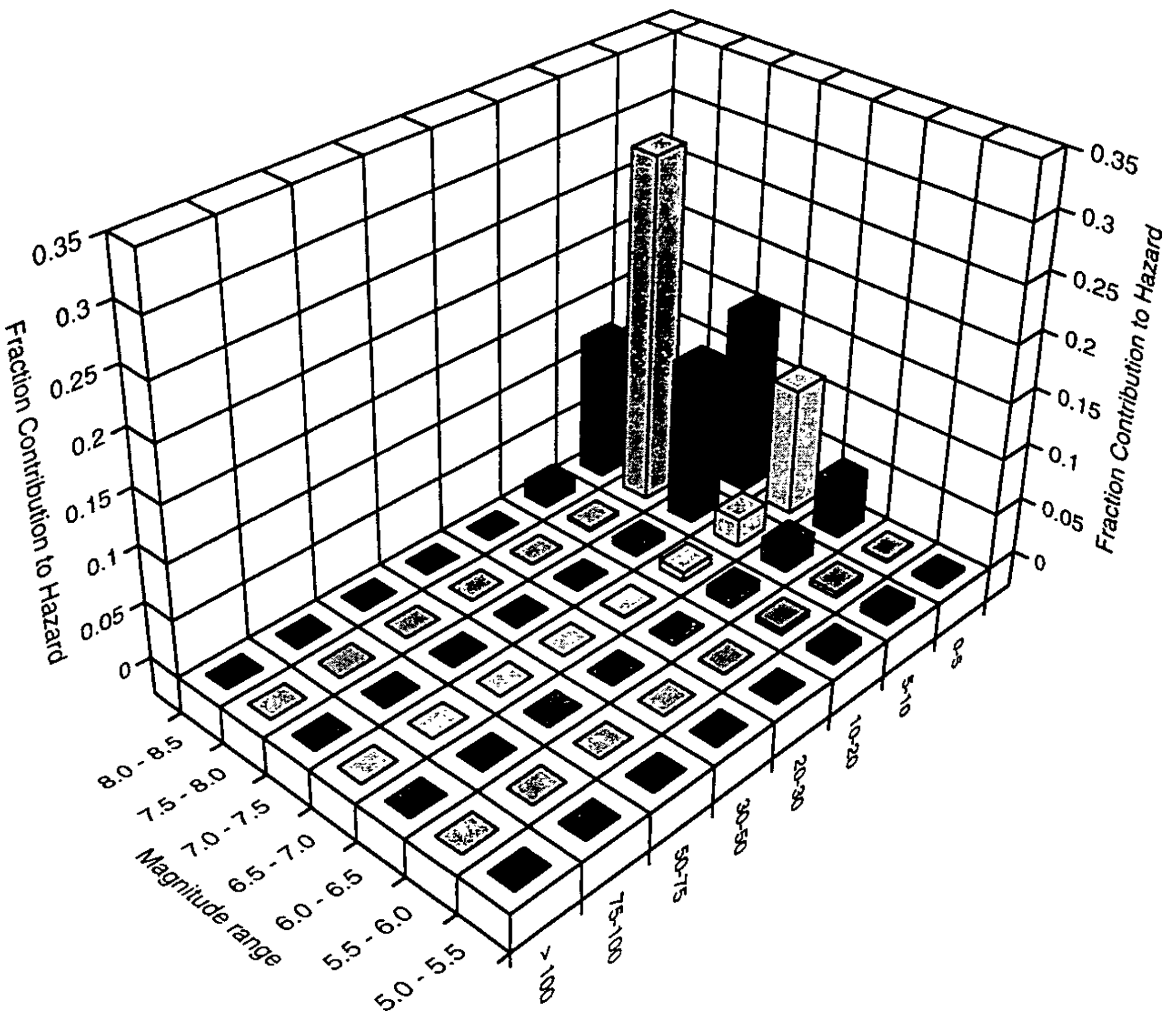
Peak Acceleration
72 year return period



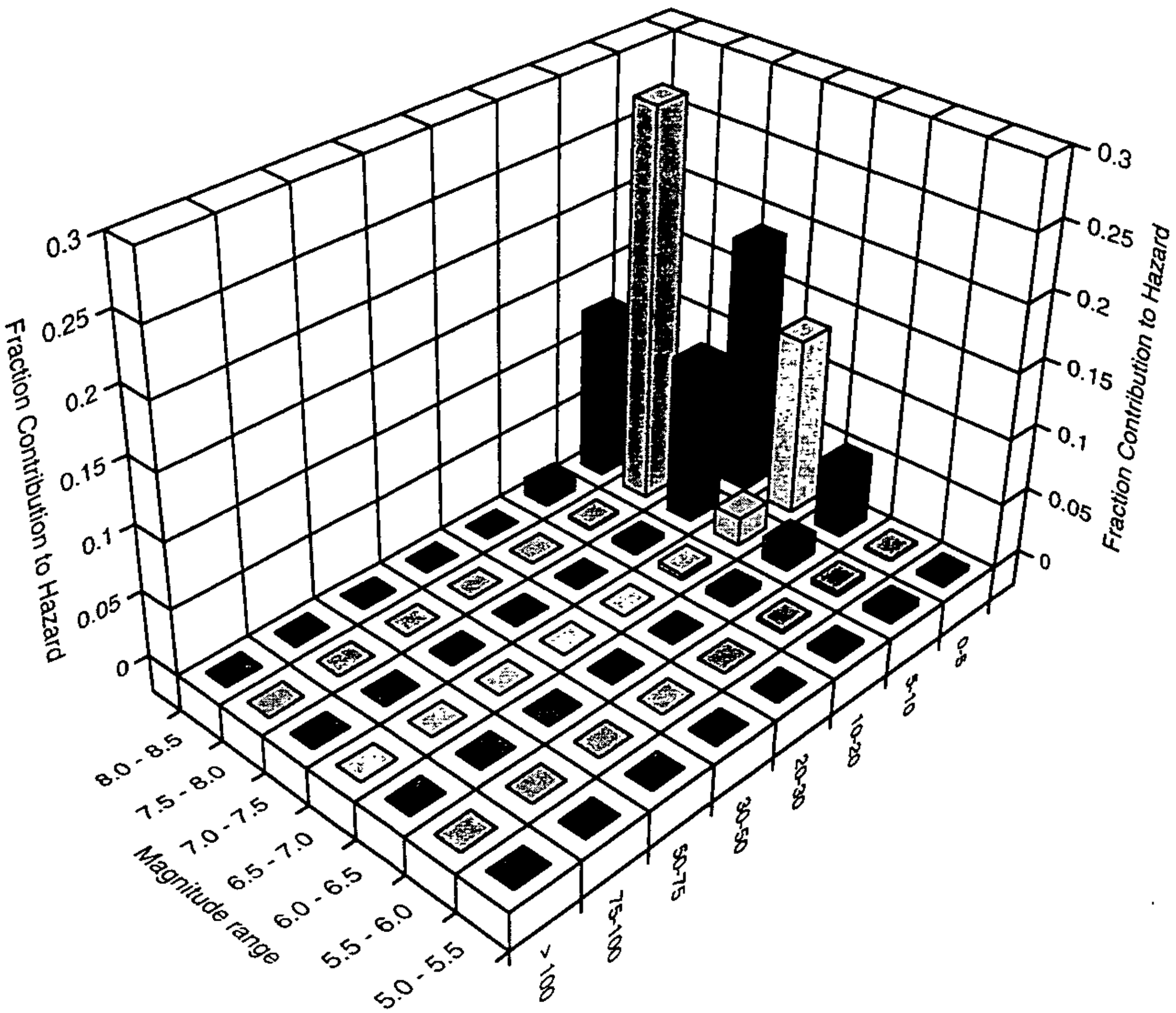
Peak Acceleration
100 year return period



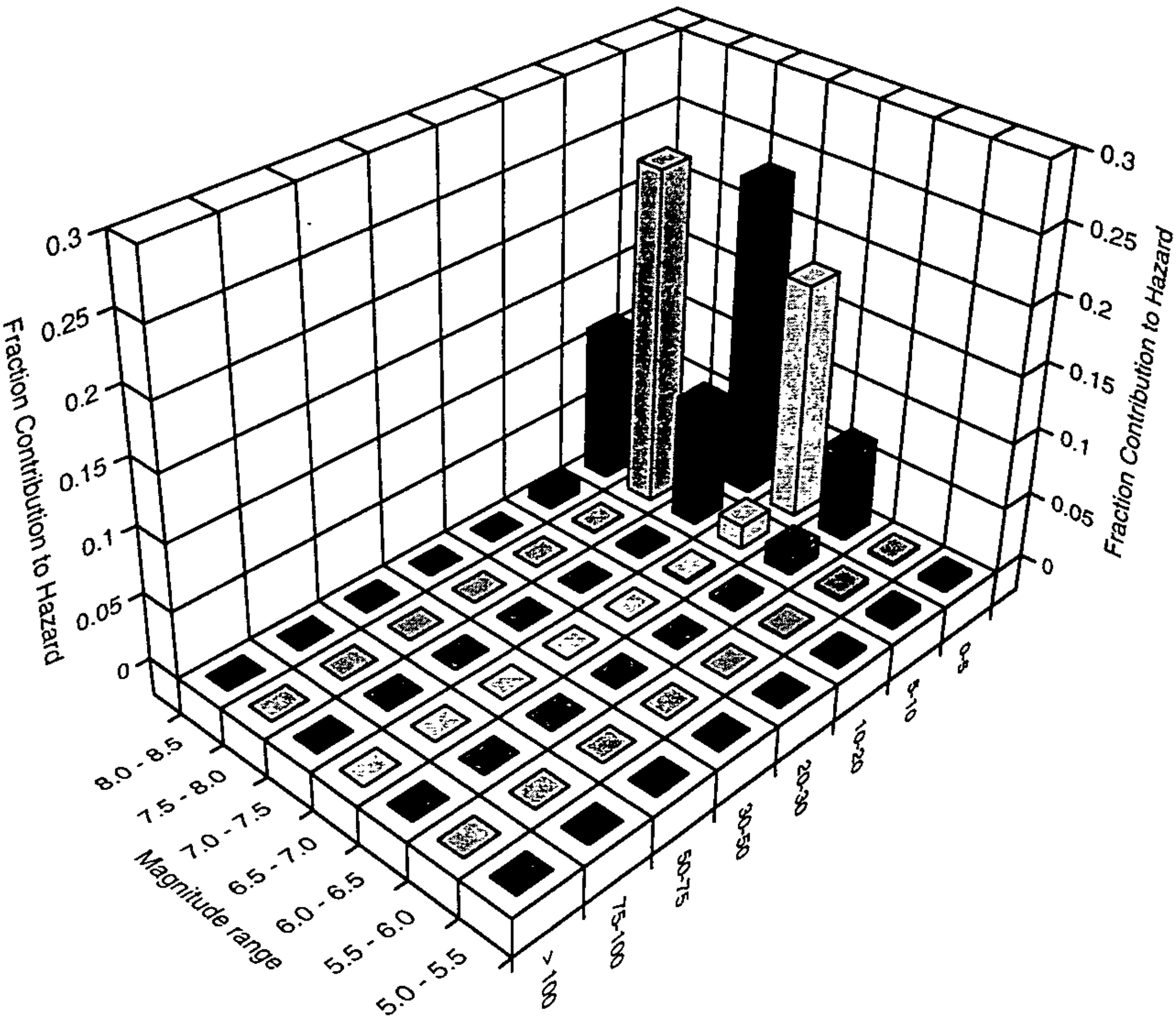
Peak Acceleration
200 year return period



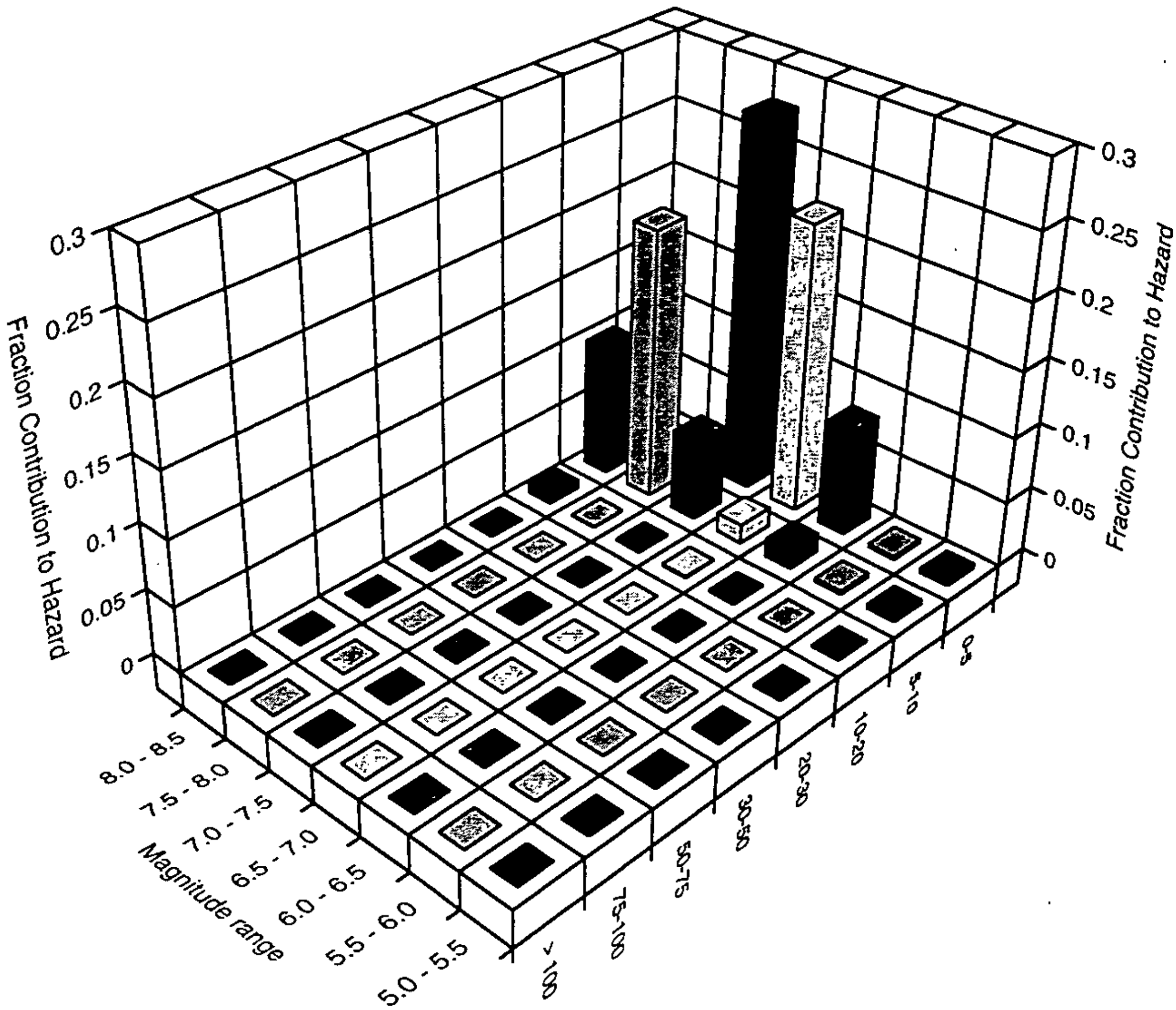
Peak Acceleration
500 year return period



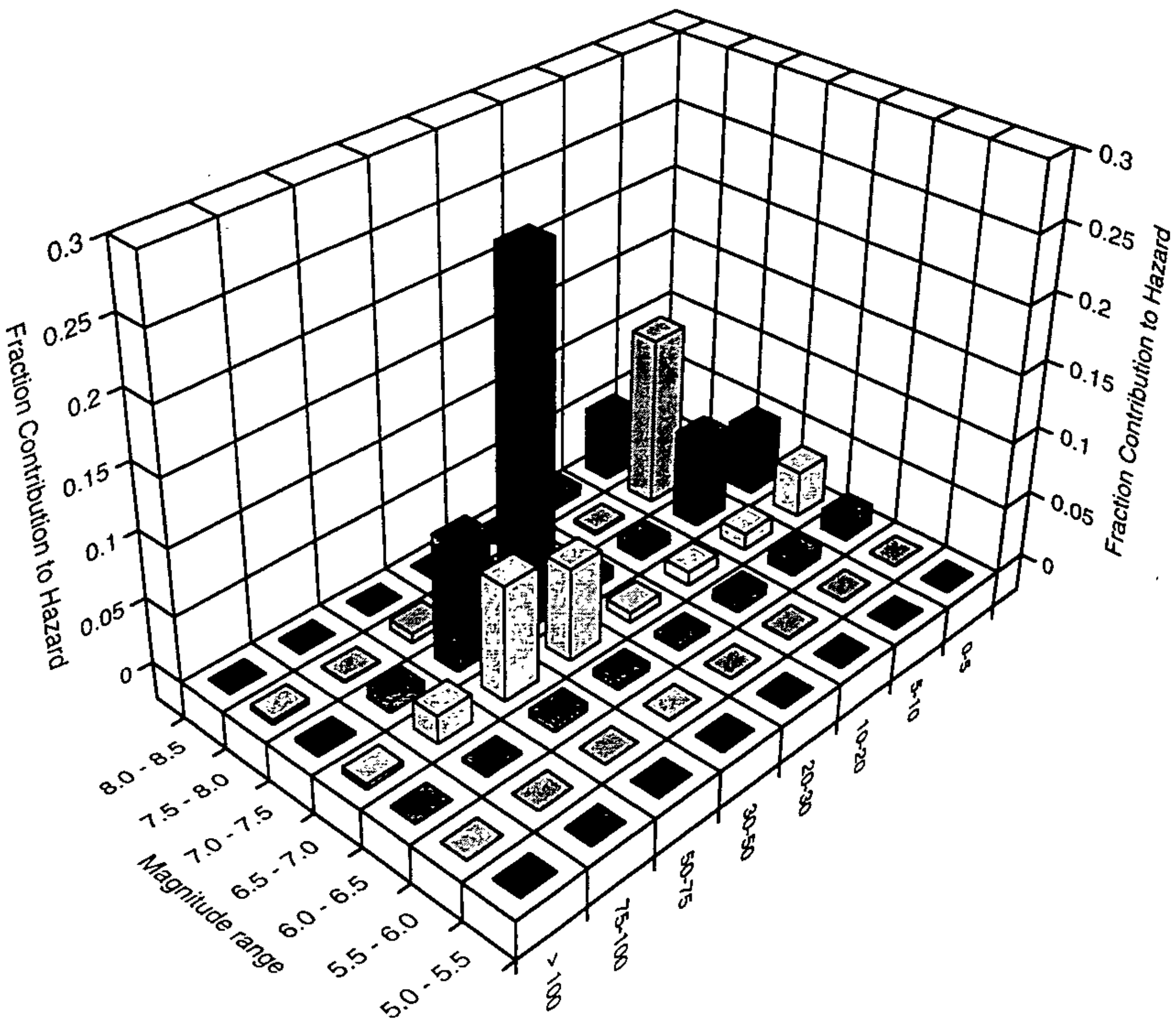
Peak Acceleration
1000 year return period



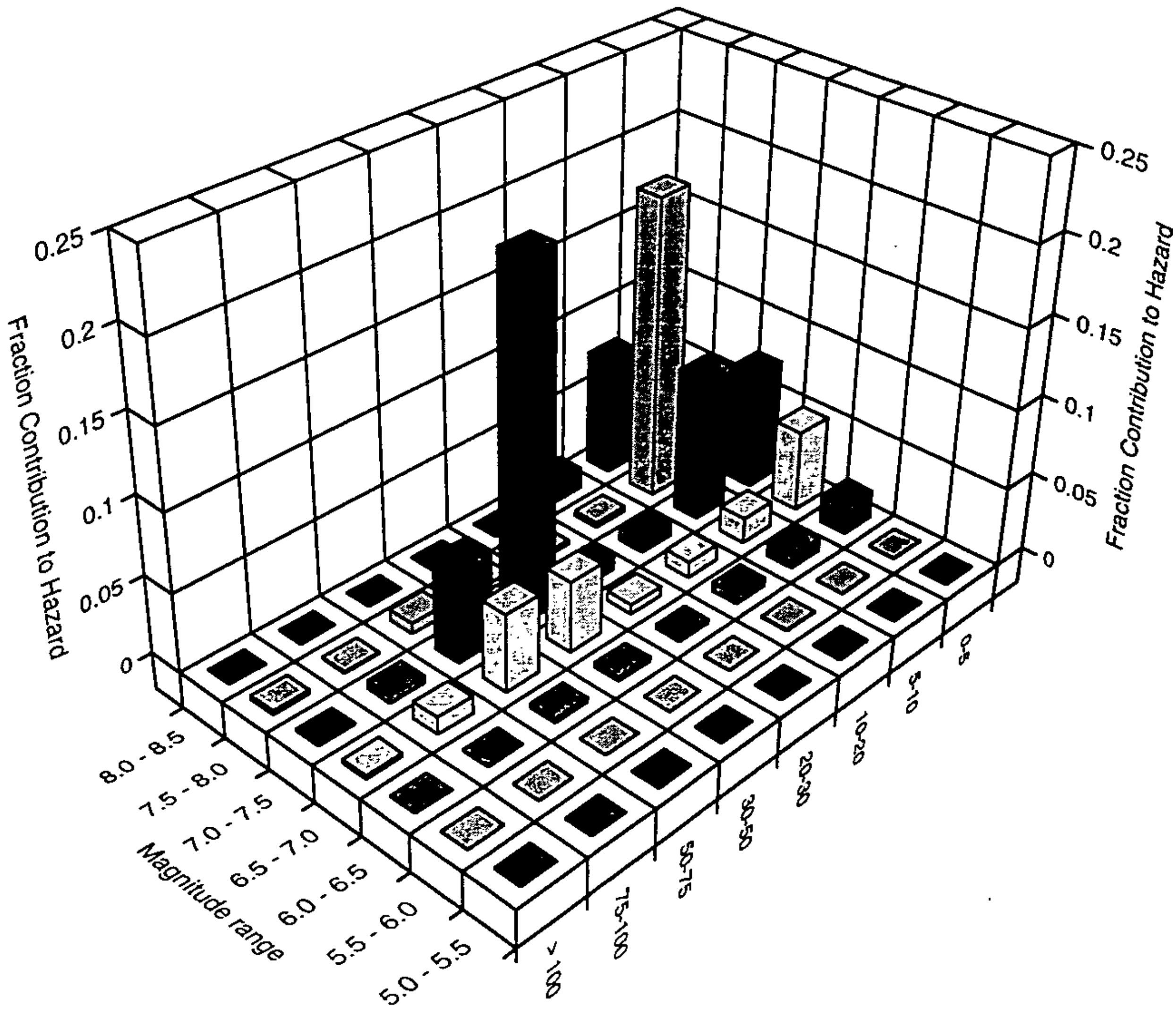
Peak Acceleration
2500 year return period



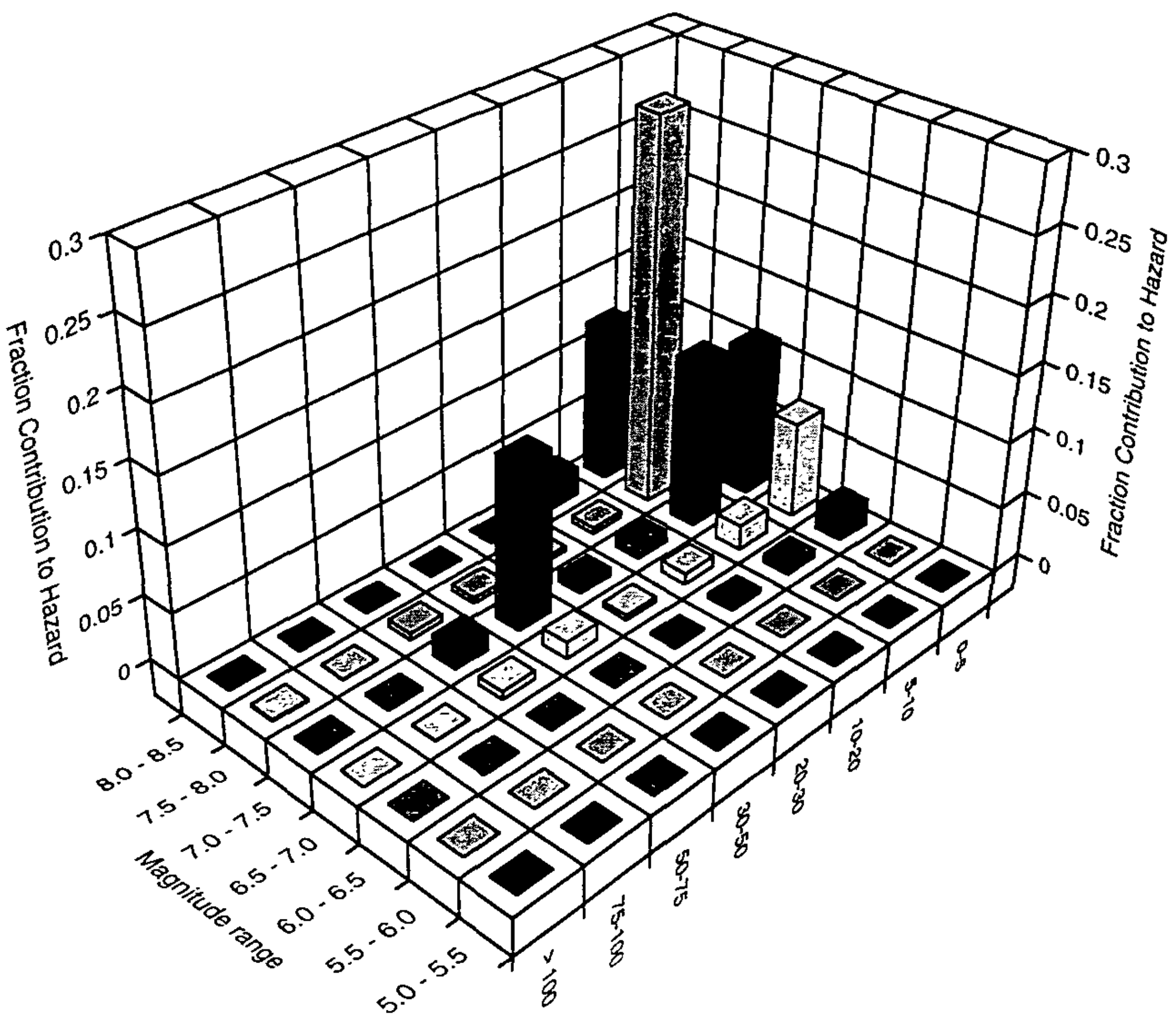
T=3 sec Spectral Acceleration
72 year return period



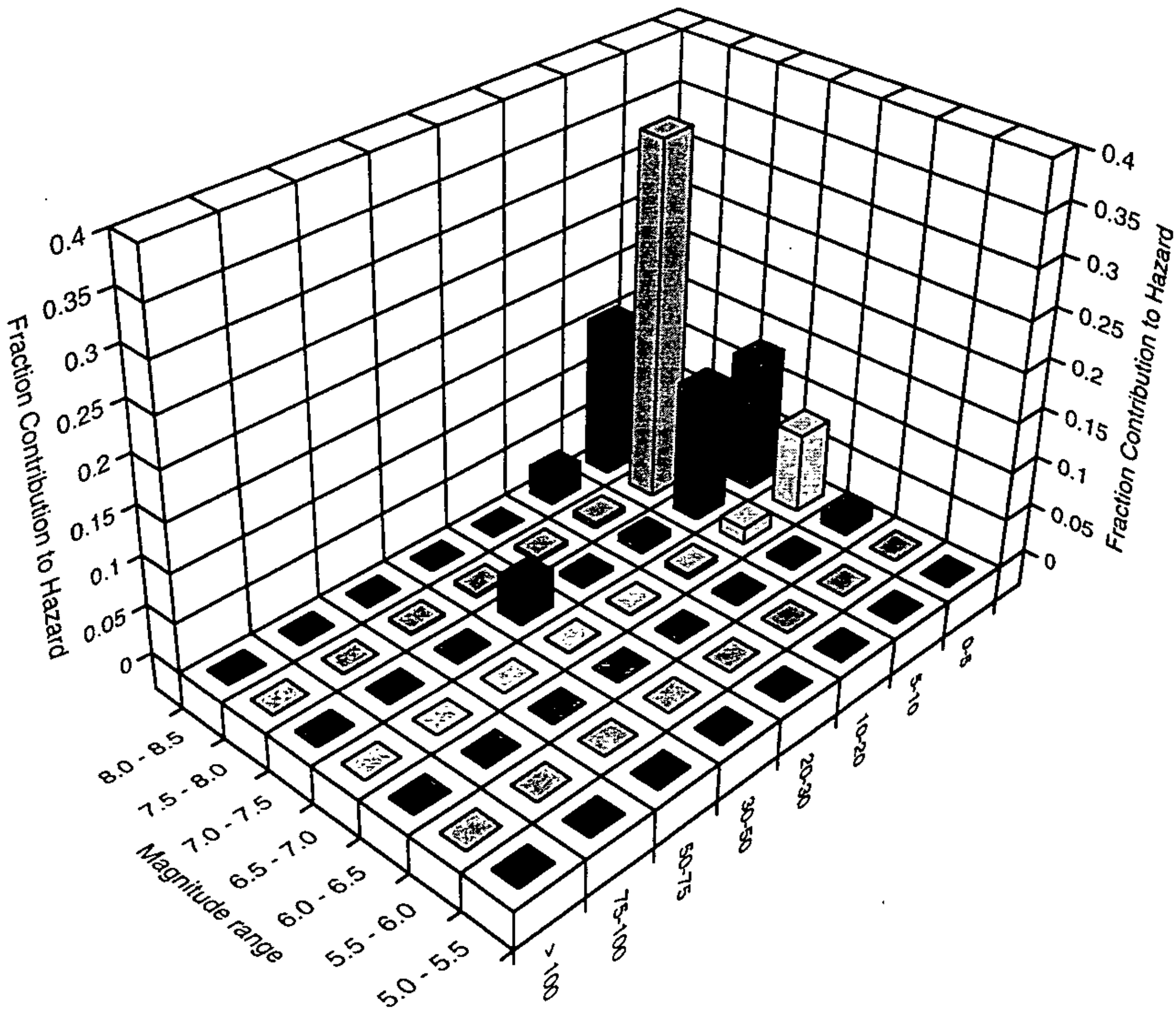
T=3 sec Spectral Acceleration
100 year return period



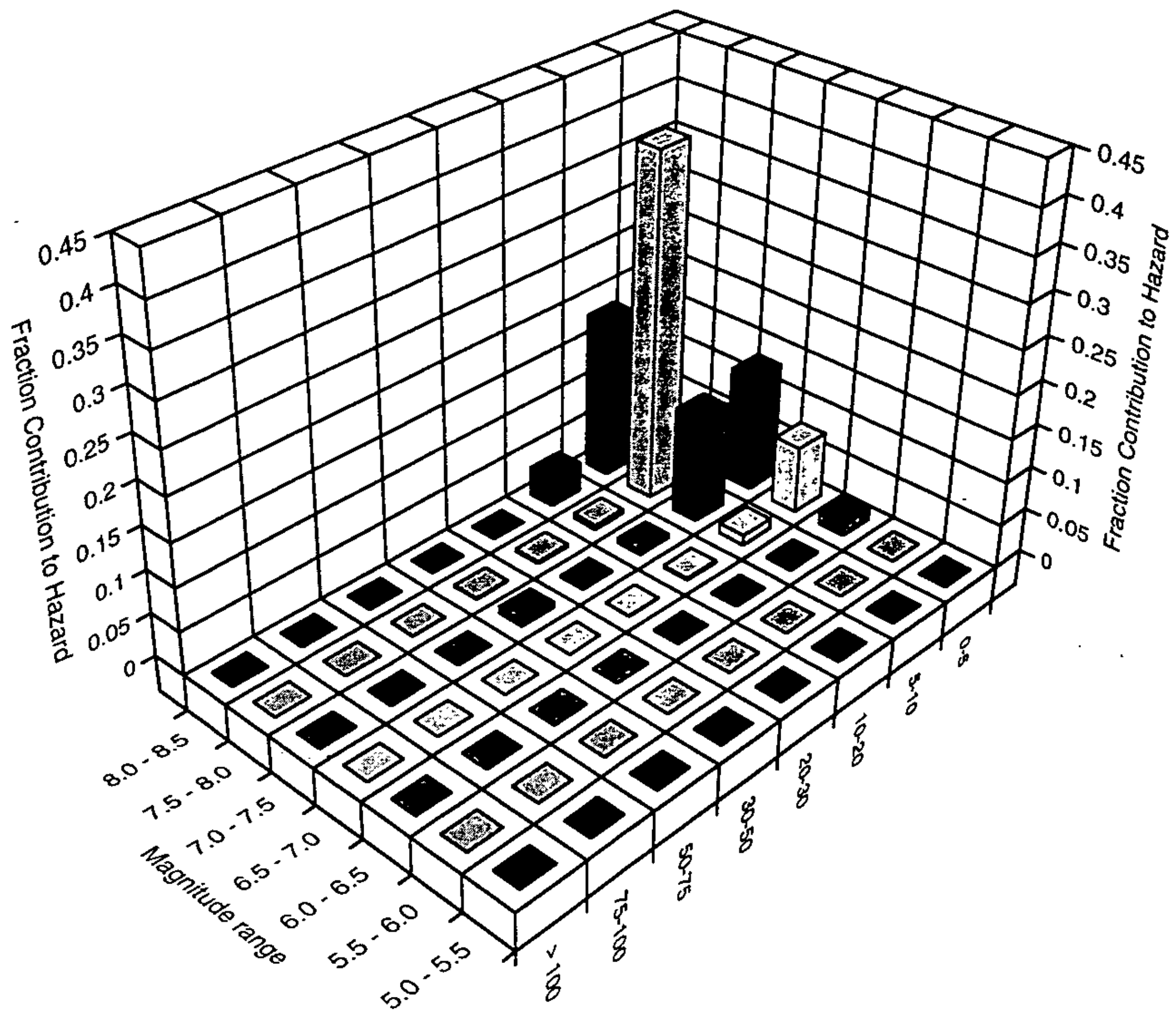
T=3 sec Spectral Acceleration
200 year return period



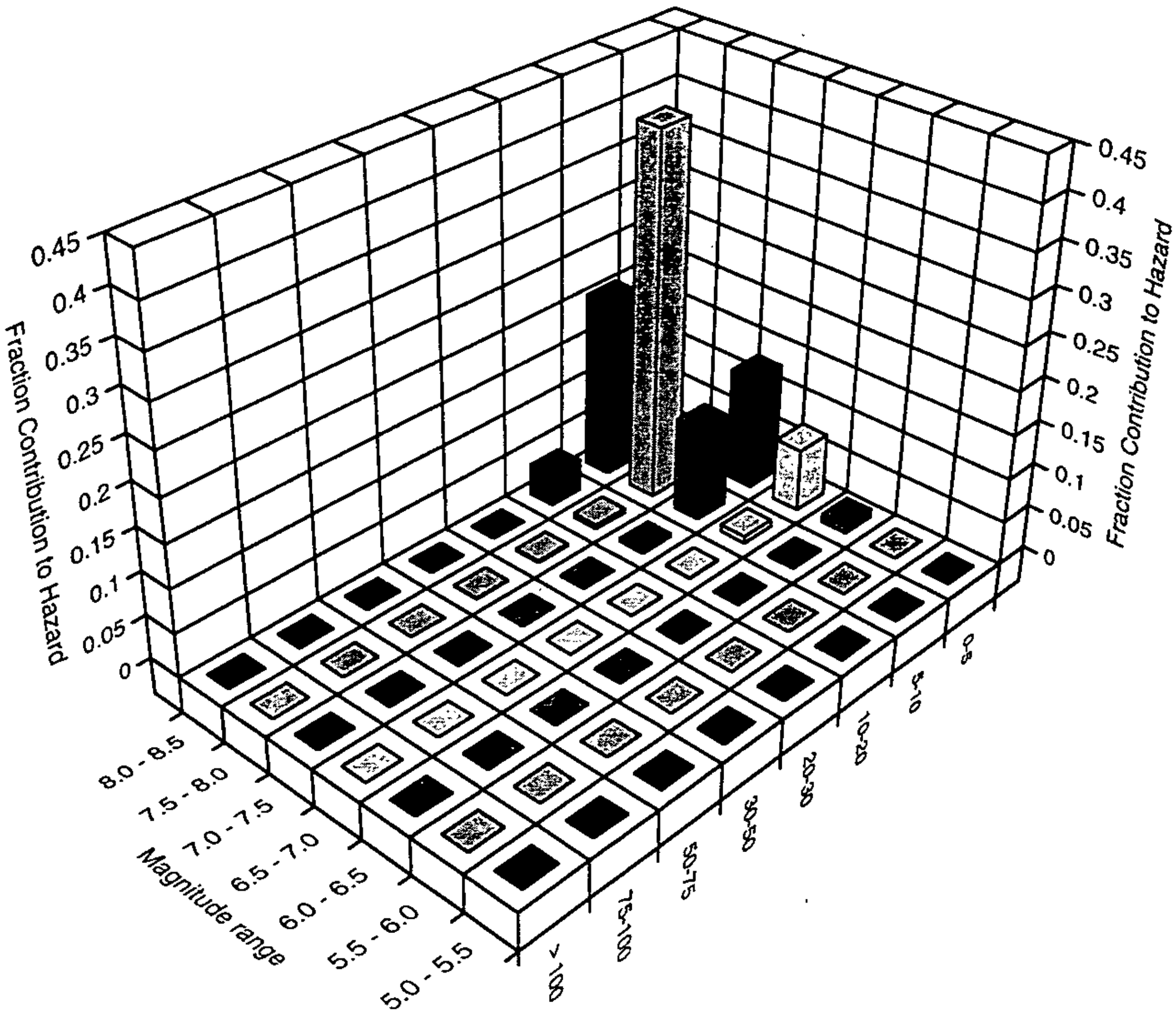
T=3 sec Spectral Acceleration
500 year return period



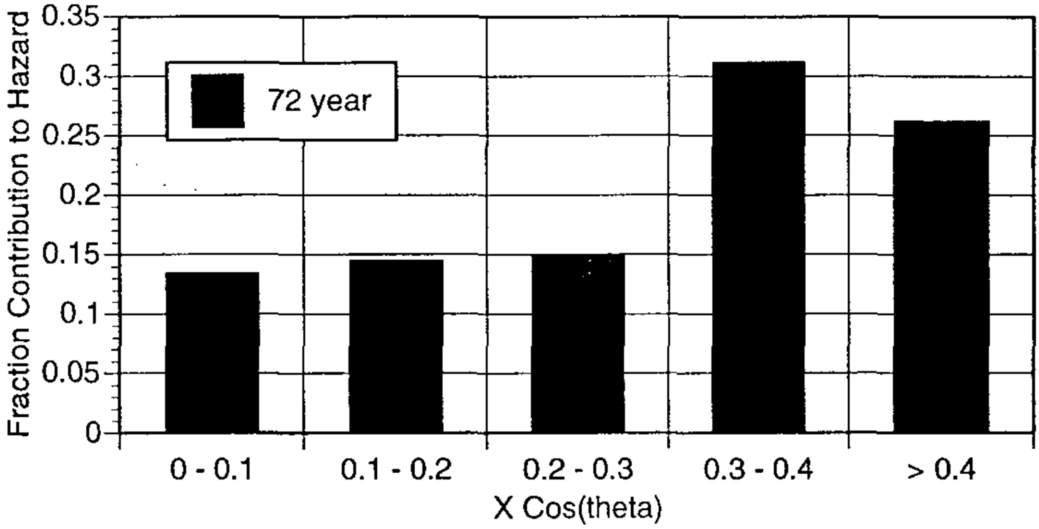
T=3 sec Spectral Acceleration
1000 year return period



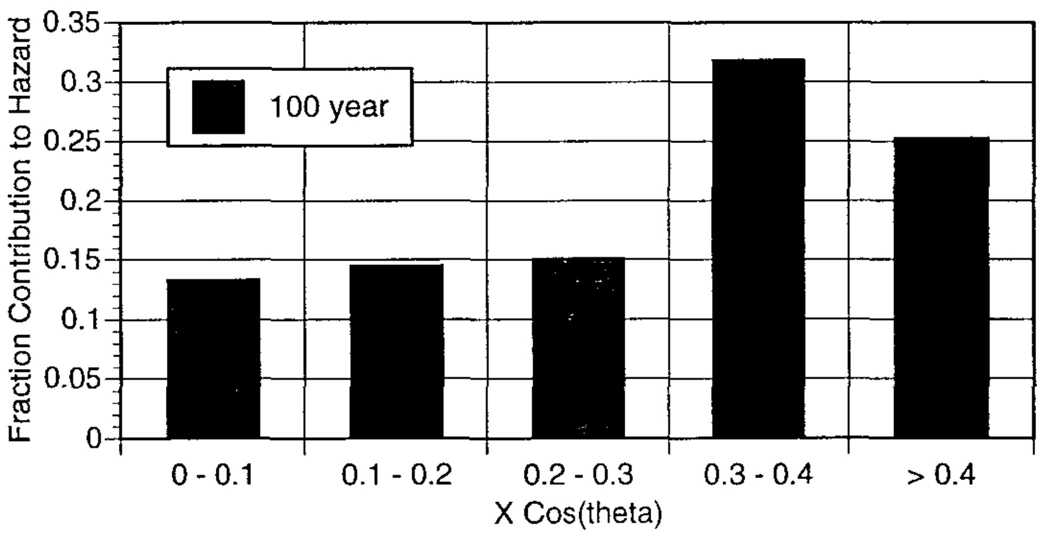
T=3 sec Spectral Acceleration
2500 year return period



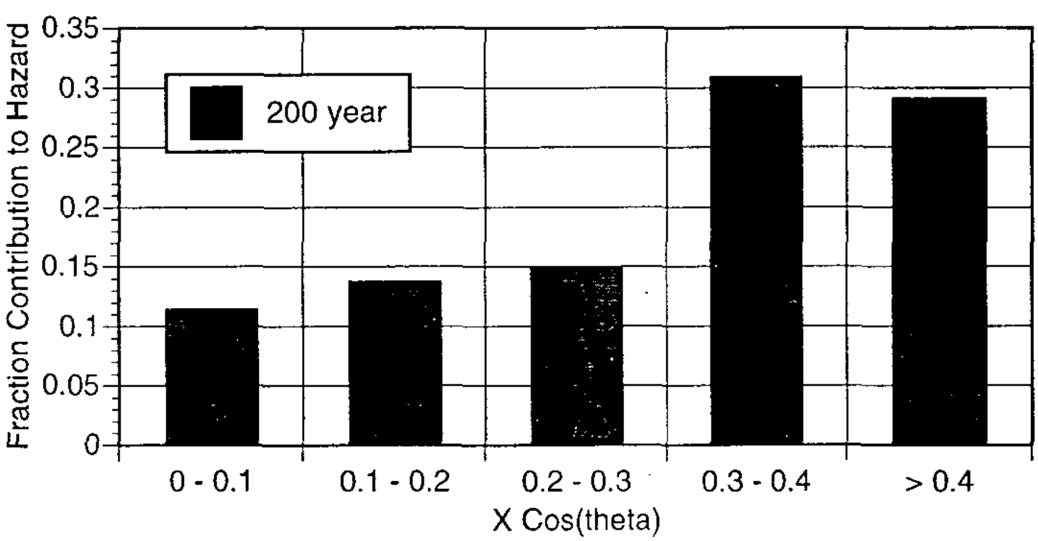
T = 3 seconds



Fraction Contribution to Hazard
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
72 year
0 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
> 0.4
X Cos(theta)

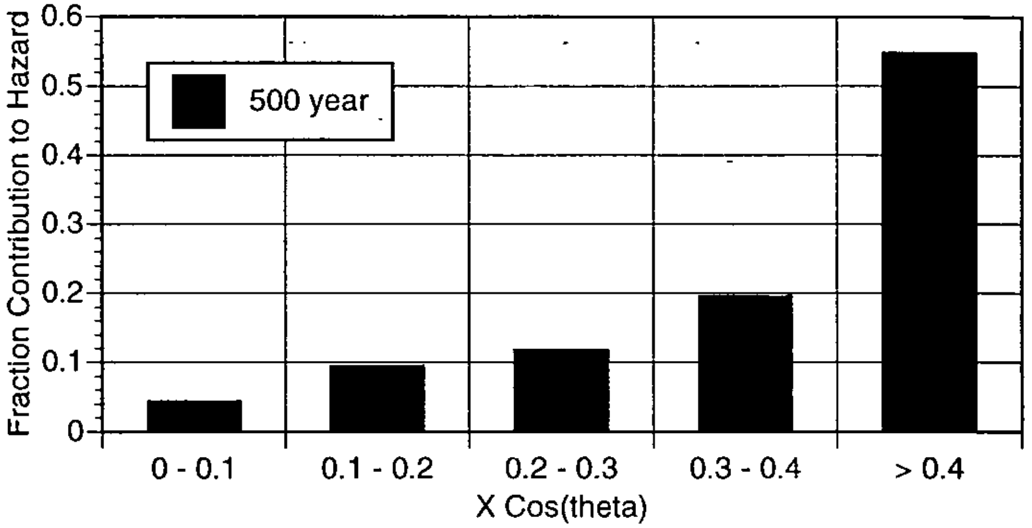


Fraction Contribution to Hazard
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
100 year
0 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
> 0.4
X Cos(theta)

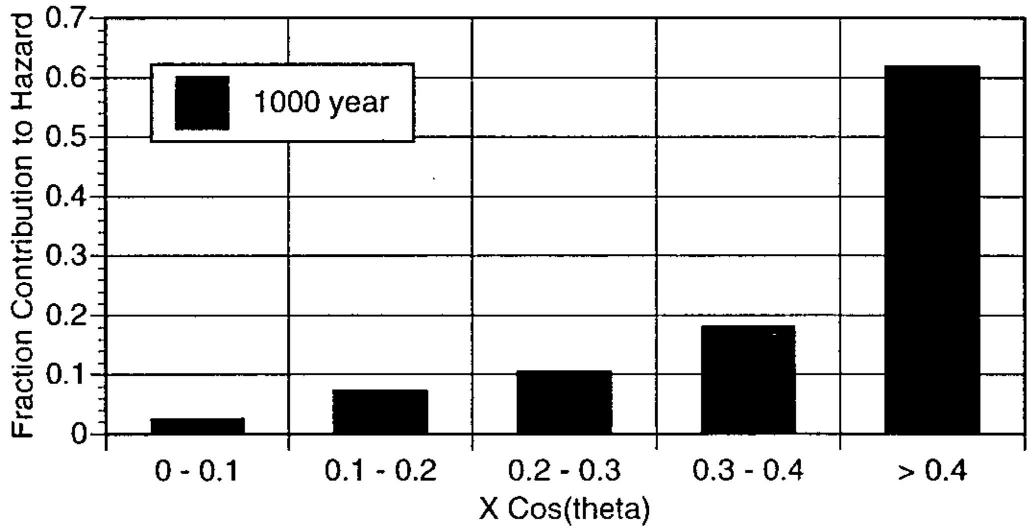


Fraction Contribution to Hazard
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
200 year
0 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
> 0.4
X Cos(theta)

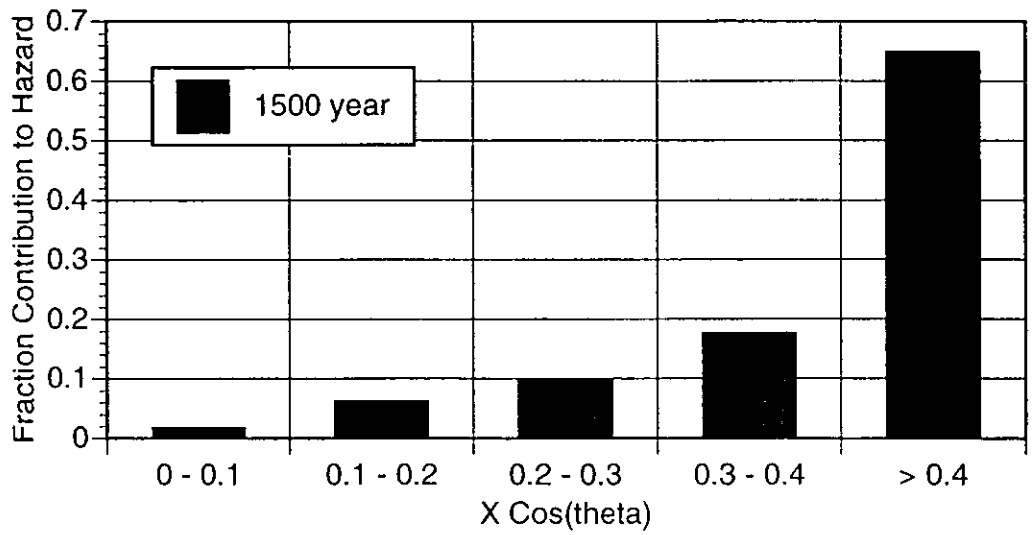
T = 3 seconds



500 year
Fraction Contribution to Hazard
0.6
0.5
0.4
0.3
0.2
0.1
0
0 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
> 0.4
X Cos(theta)

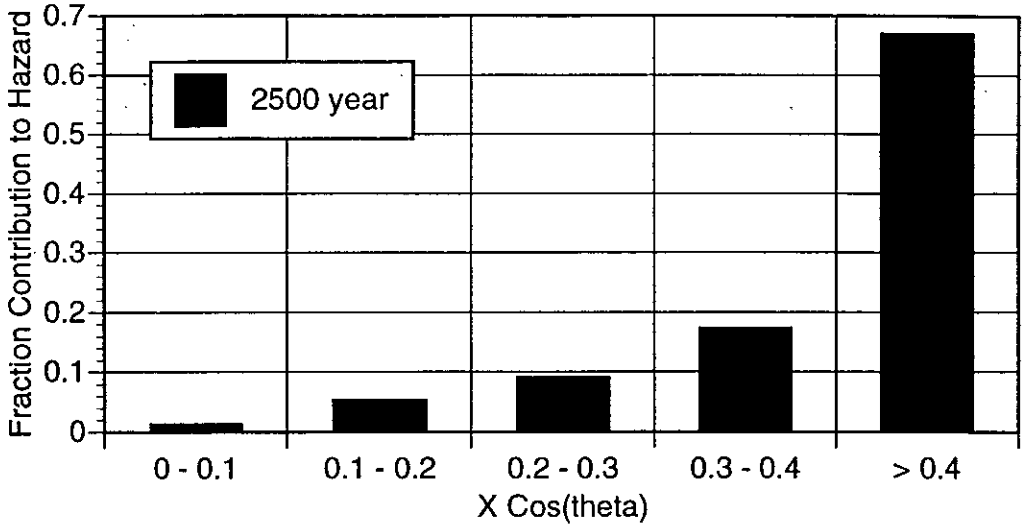


1000 year
Fraction Contribution to Hazard
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
> 0.4
X Cos(theta)

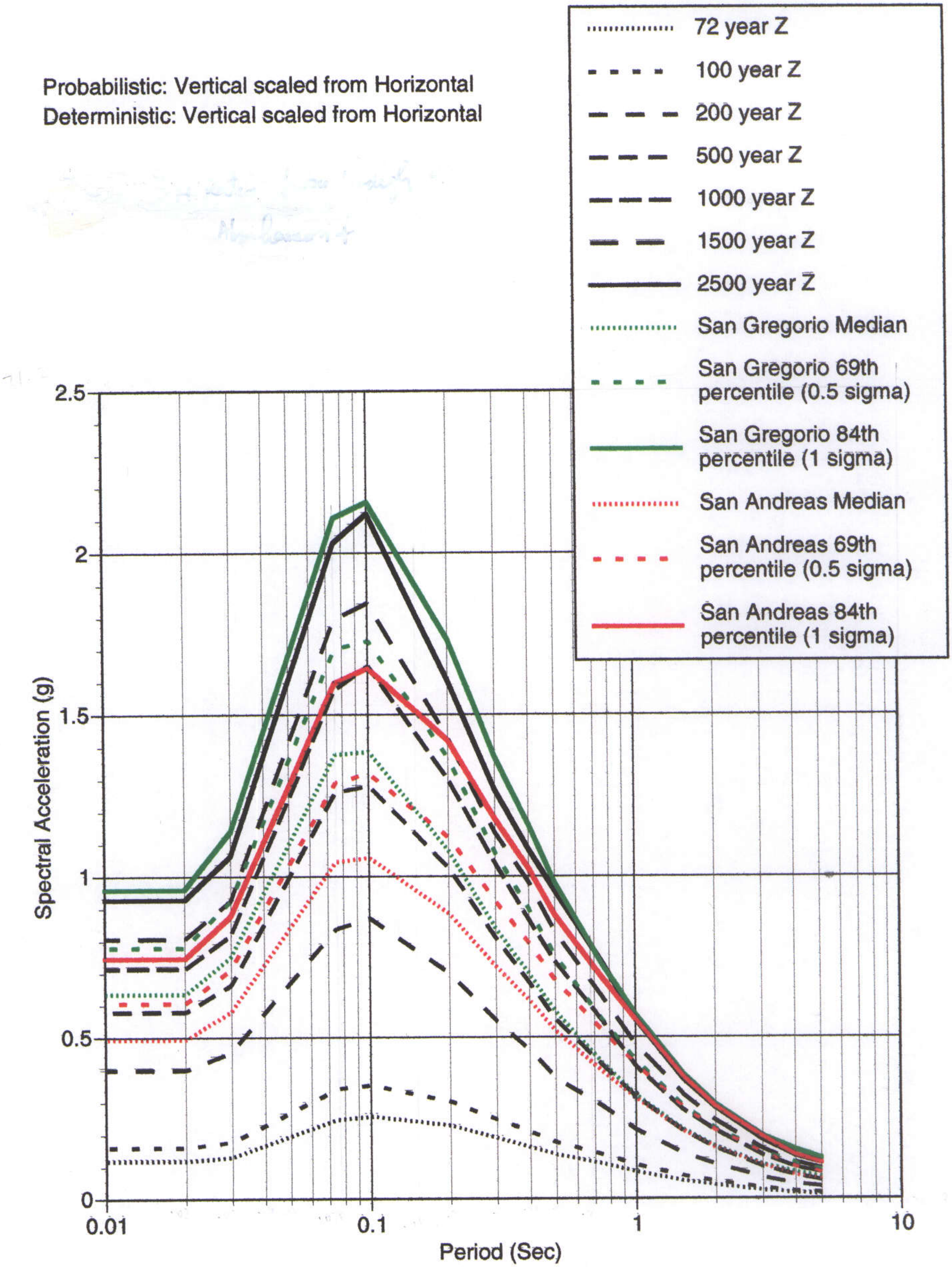


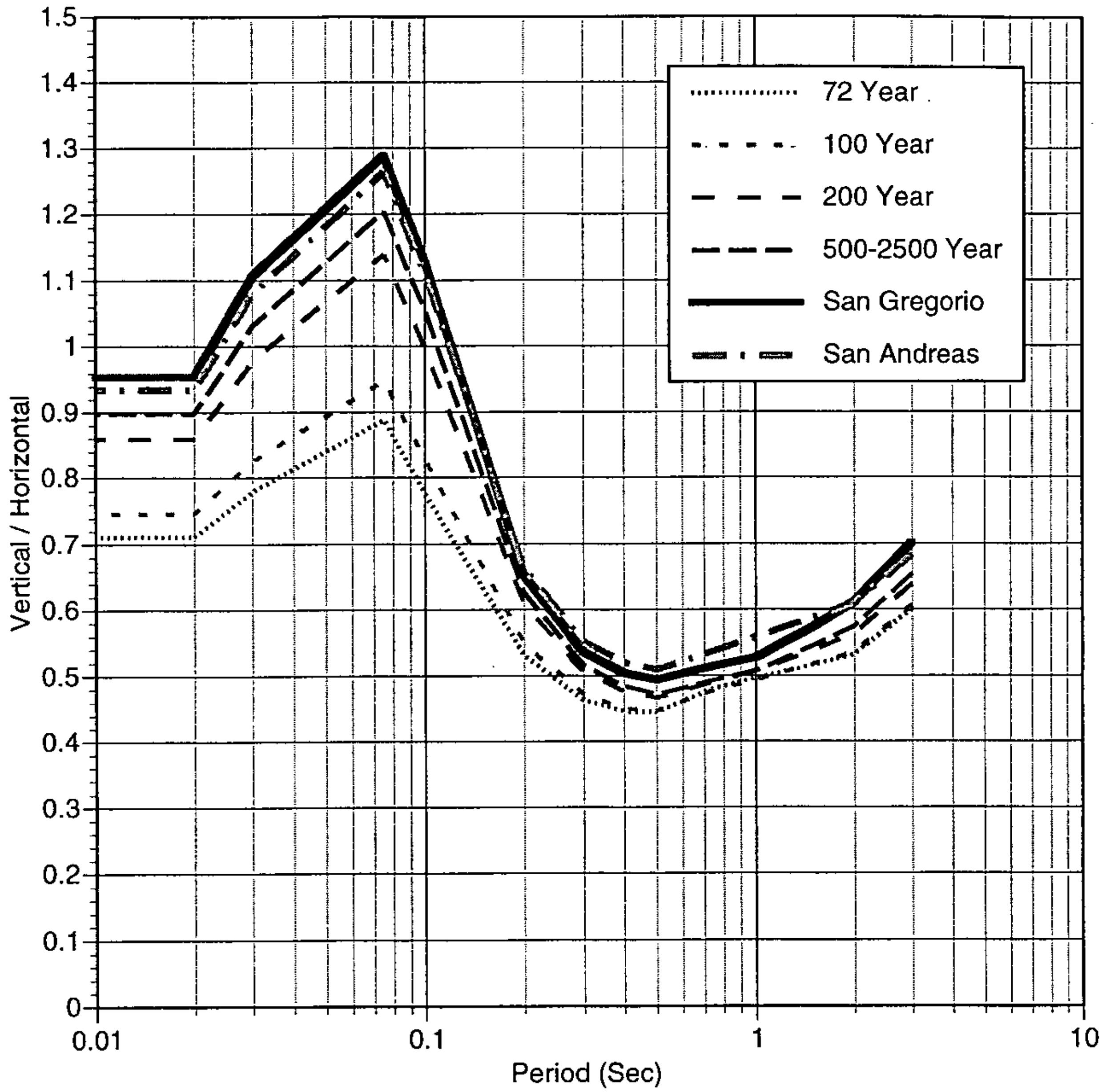
1500 year
Fraction Contribution to Hazard
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
> 0.4
X Cos(theta)

T = 3 seconds



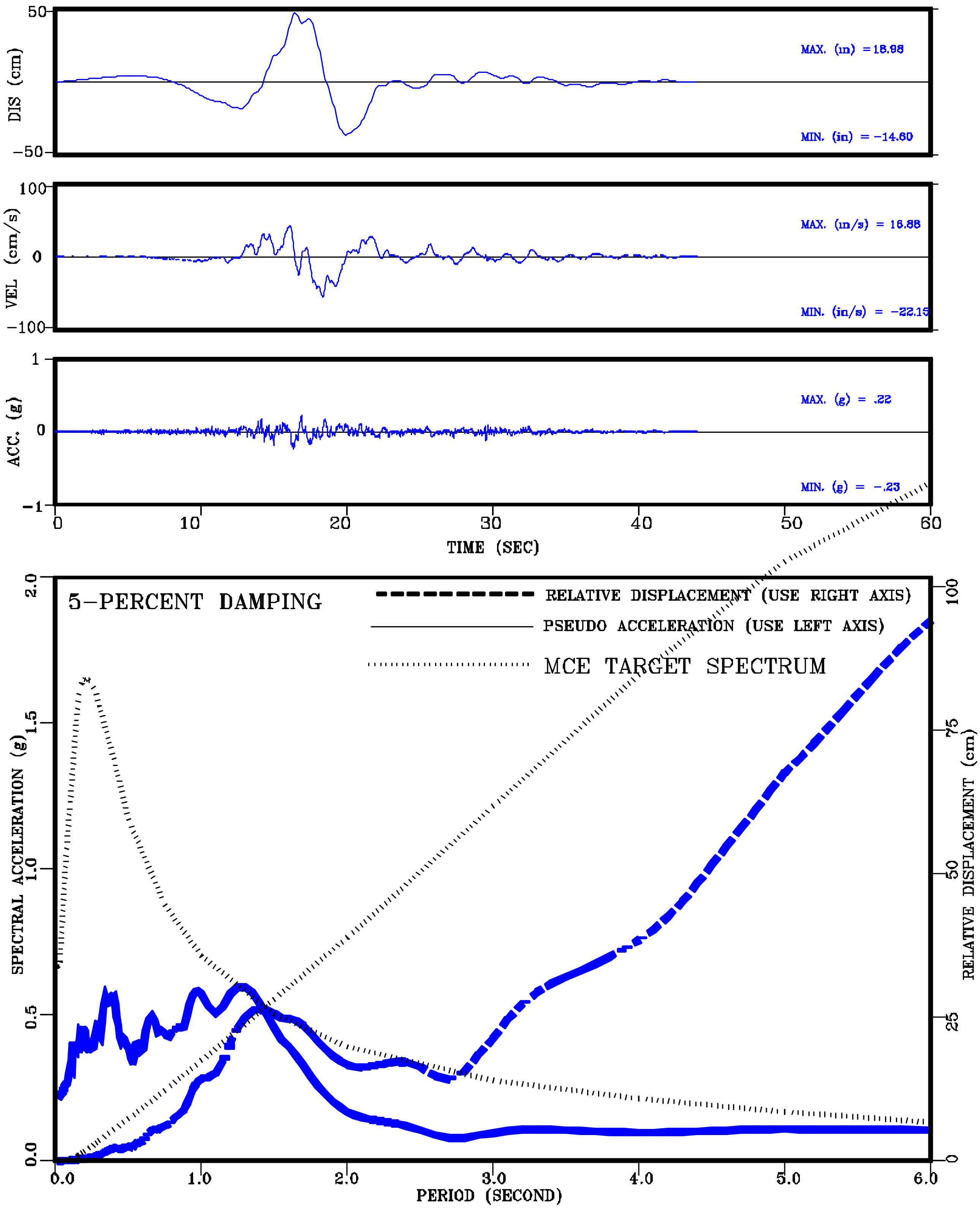
Fraction Contribution to Hazard
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
2500 year
0 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
> 0.4
X Cos(theta)


Probabilistic: Vertical scaled from Horizontal
Deterministic: Vertical scaled from Horizontal
72 year Z
100 year Z
200 year Z
500 year Z
1000 year Z
1500 year Z
2500 year Z
San Gregorio Median
San Gregorio 69th percentile (0.5 sigma)
San Gregorio 84th percentile (1 sigma)
San Andreas Median
San Andreas 69th percentile (0.5 sigma)
San Andreas 84th percentile (1 sigma)
Spectral Acceleration (g)
2.5
2
1.5
1
0.5
0
0.01
0.1
1
10
Period (Sec)



1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Vertical / Horizontal
0.01
0.1
1
10
Period (Sec)
72 Year
100 Year
200 Year
500-2500 Year
San Gregorio
San Andreas

APPENDIX B
DETAILS OF START-UP (EMPIRICAL) MOTIONS



Earth Mechanics, Inc.

Geotechnical and Earthquake Engineering

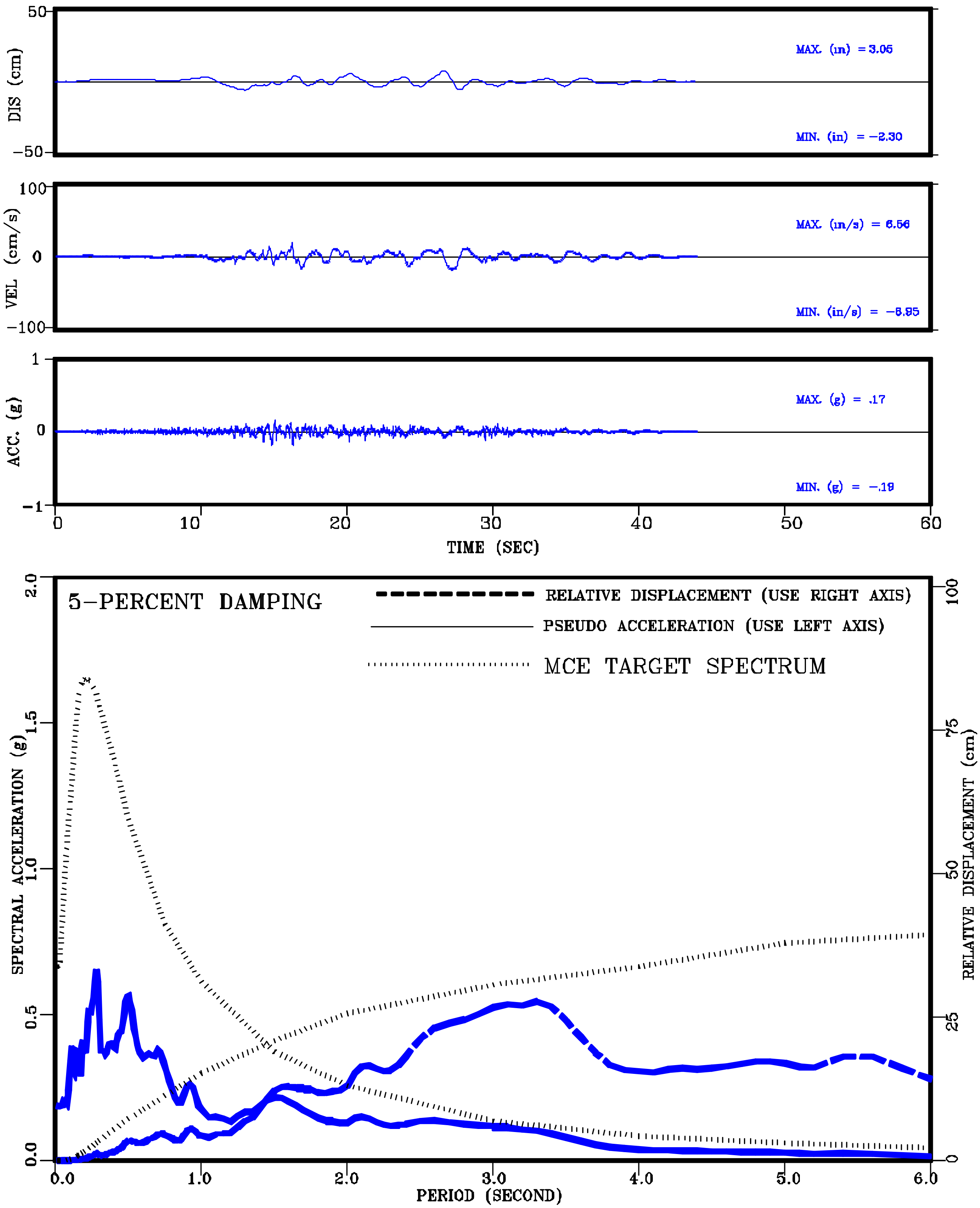
DEVIL'S SLIDE TUNNELS

EMI Project No.: 01-119 | Date: 8/20/01

YERMO MAJOR PRINC. COMP. MOTION

STARTUP FOR SET 1 FN ROCK MOTION

FIGURE B-1



Earth Mechanics, Inc.

Geotechnical and Earthquake Engineering

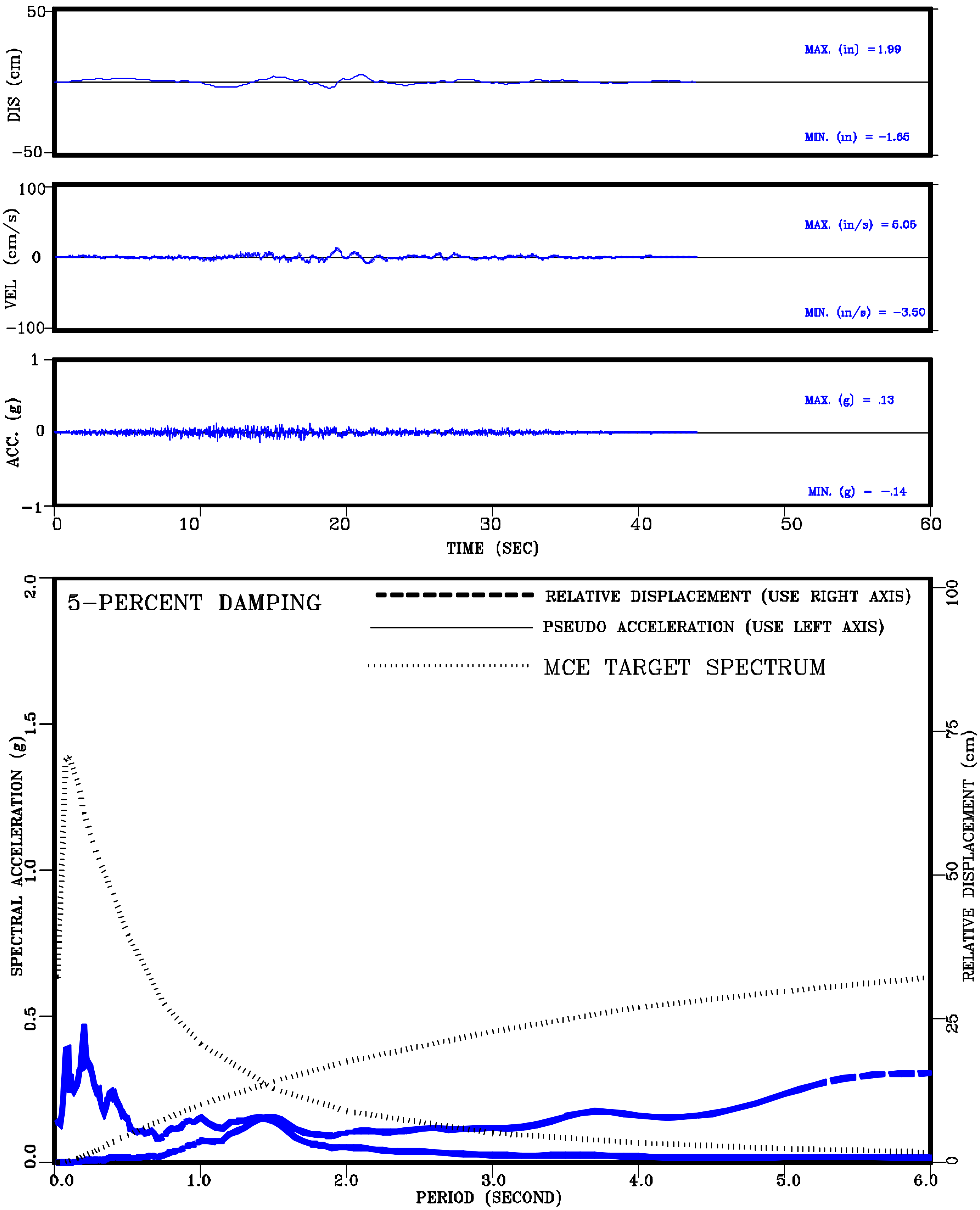
DEVIL'S SLIDE TUNNELS

EMI Project No.: 01-119 | Date: 8/20/01

YERMO MINOR PRINCIPAL COMP MOTION

STARTUP FOR SET 1 FP ROCK MOTION

FIGURE B-2



Earth Mechanics, Inc.

Geotechnical and Earthquake Engineering

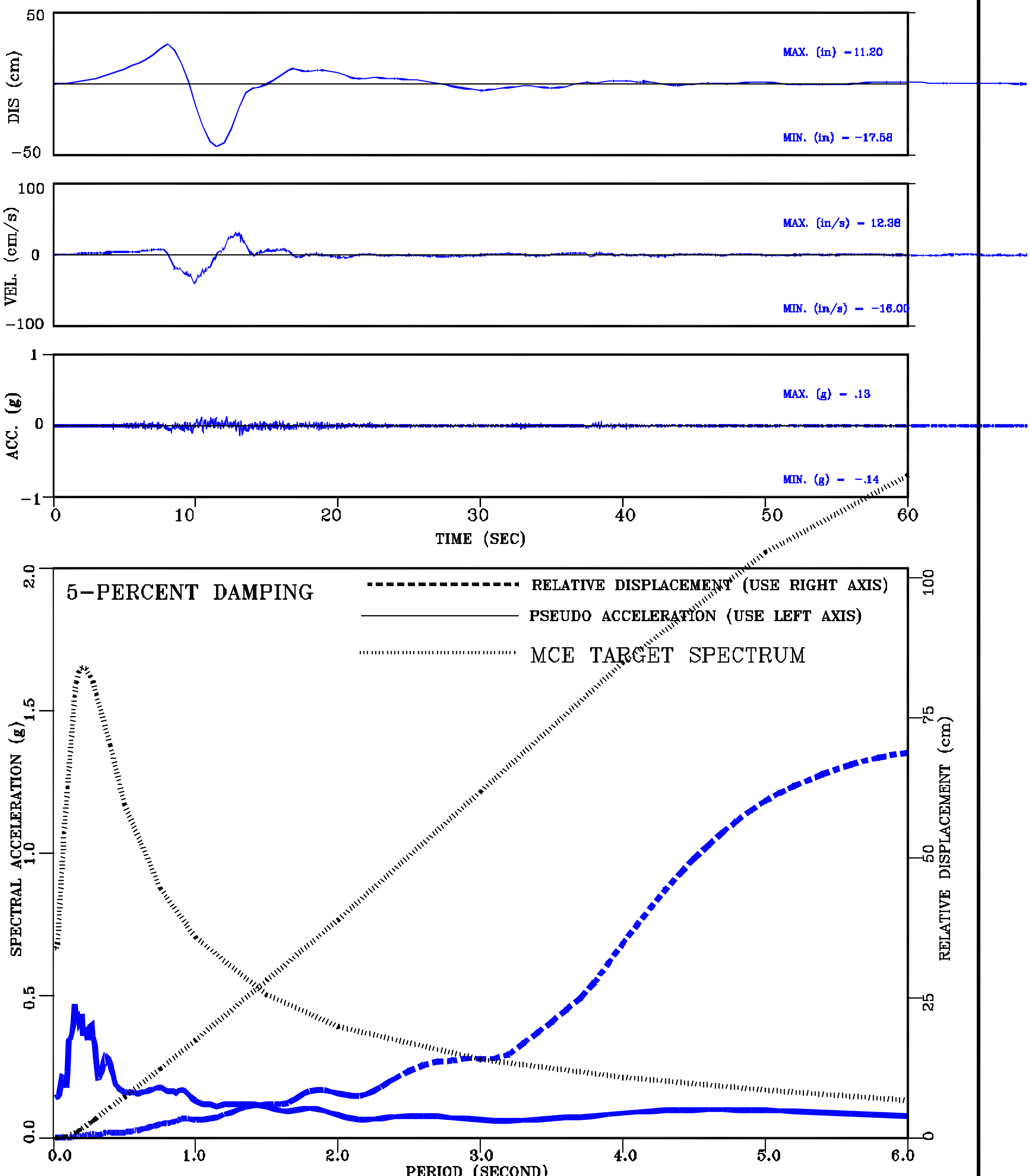
DEVIL'S SLIDE TUNNELS

EMI Project No.: 01-119 | Date: 8/20/01

YERMO VERT. COMP. MOTION

STARTUP FOR SET 1 VERT. ROCK MOTION

FIGURE B-3



Earth Mechanics, Inc.

Geotechnical and Earthquake Engineering

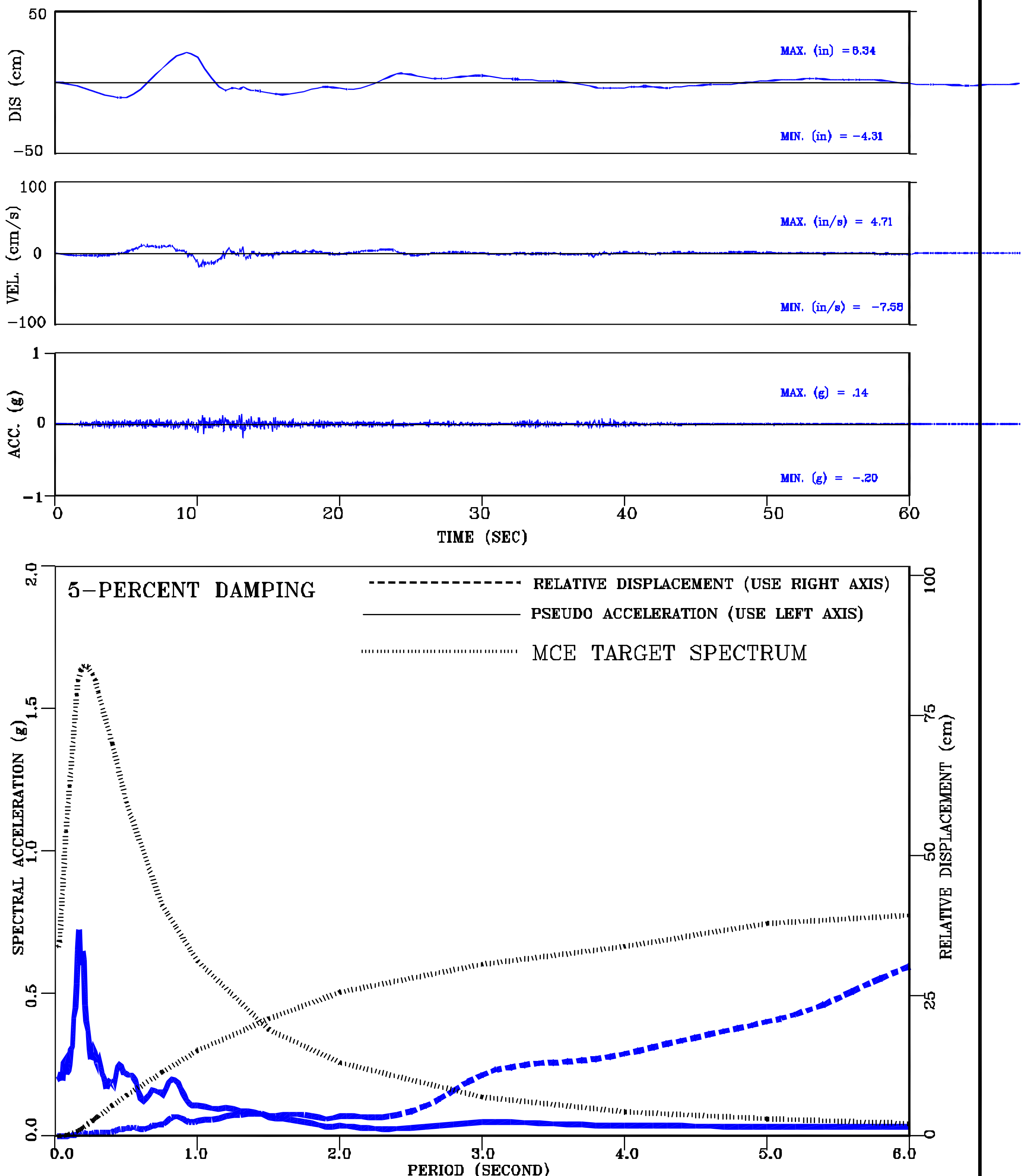
DEVIL'S SLIDE TUNNELS

EMI Project No.: 01-119 | Date: 8/20/01

ARCELIK MAJOR PRINC. COMPONENT MOTION

STARTUP FOR 2 FN ROCK MOTION

FIGURE B-4



Earth Mechanics, Inc.

Geotechnical and Earthquake Engineering

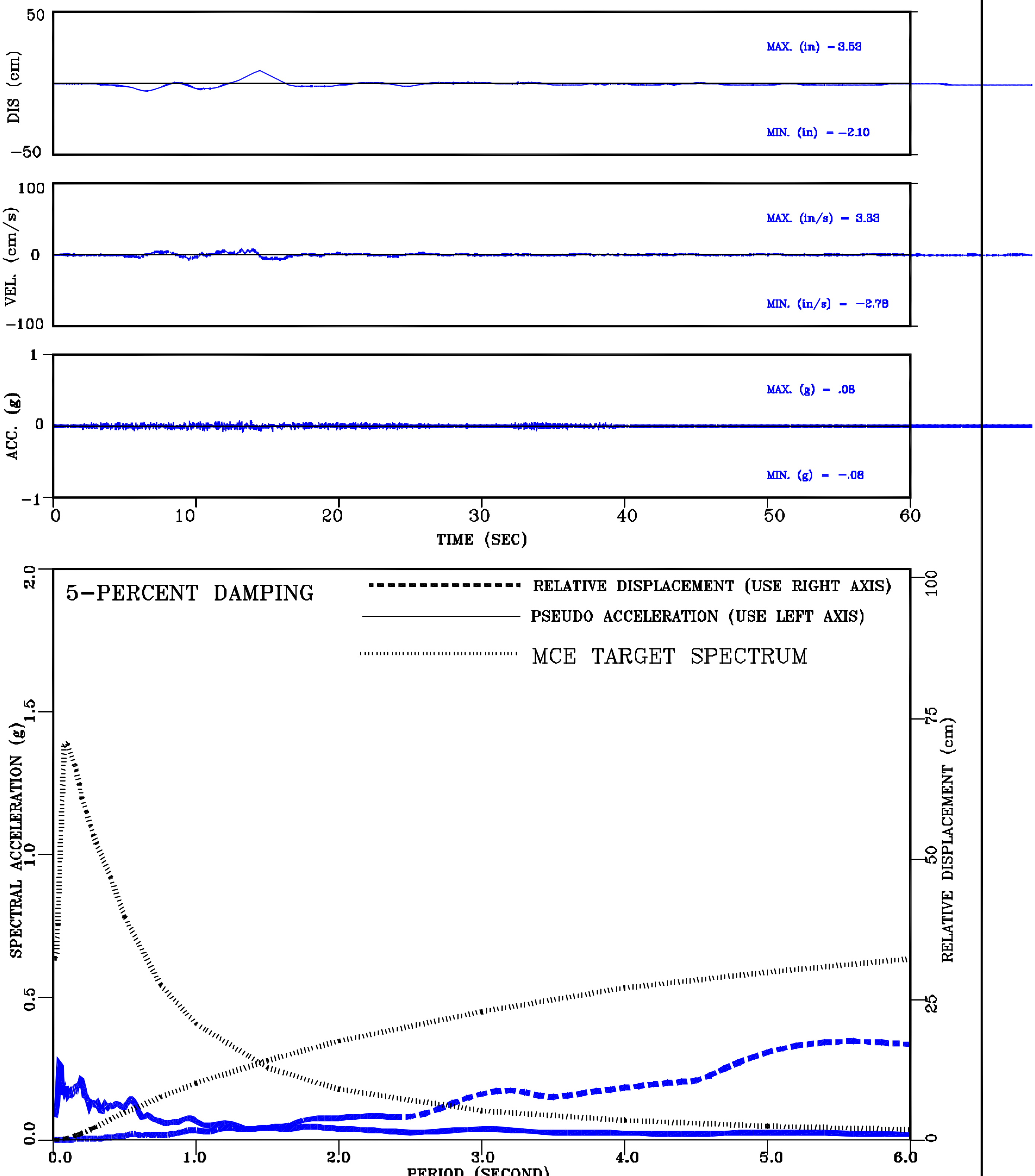
DEVIL'S SLIDE TUNNELS

EMI Project No.: 01-119 | Date: 8/20/01

ARCELIK MINOR PRINC. COMP. MOTION

STARTUP FOR SET 2 FP ROCK MOTION

FIGURE B-5



Earth Mechanics, Inc.

Geotechnical and Earthquake Engineering

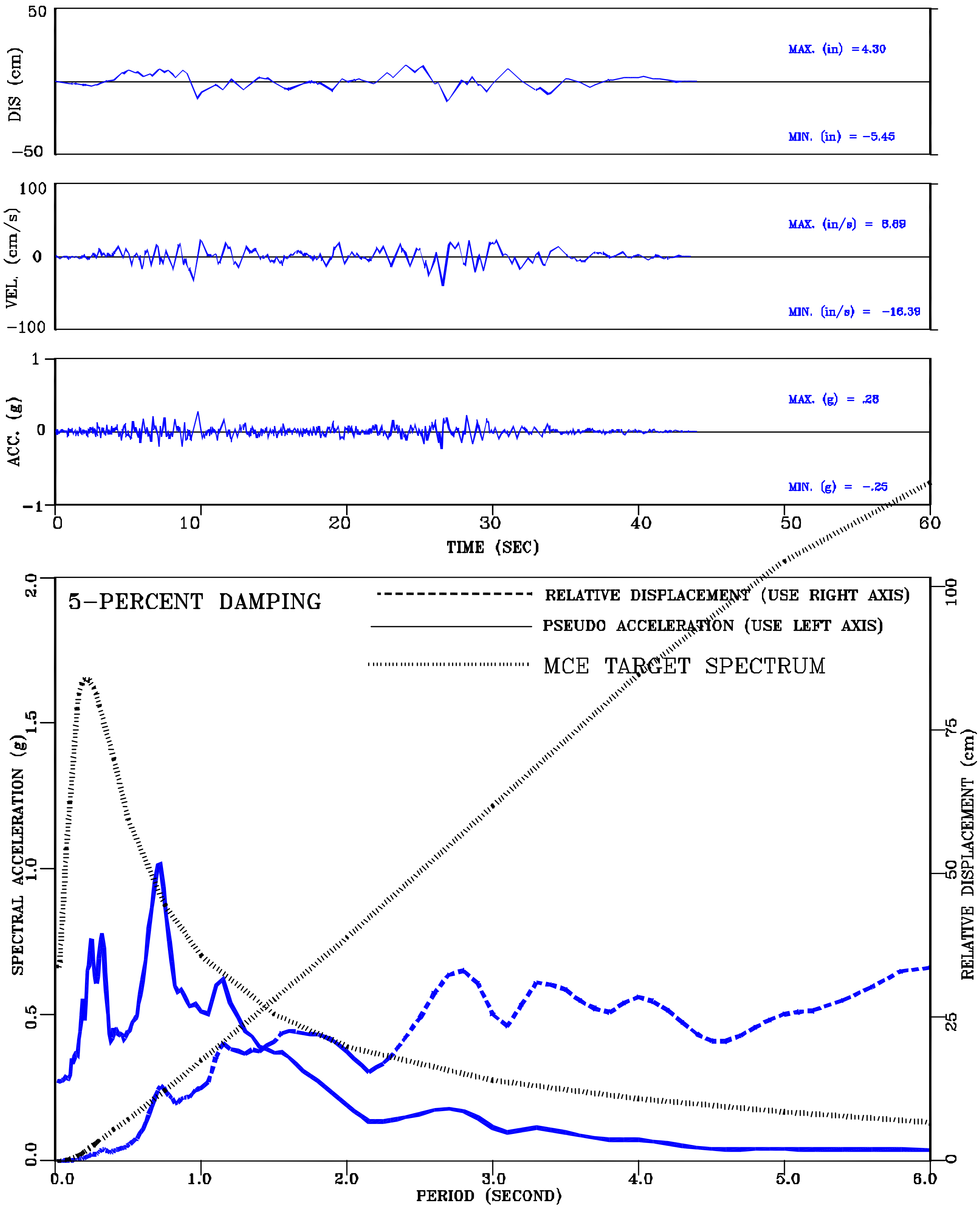
DEVIL'S SLIDE TUNNELS

EMI Project No.: 01-119 | Date: 8/20/01

ARCELIK VERTICAL COMP. MOTION

STARTUP FOR SET 2 VERT. ROCK MOTION

FIGURE B-6



Earth Mechanics, Inc.

Geotechnical and Earthquake Engineering

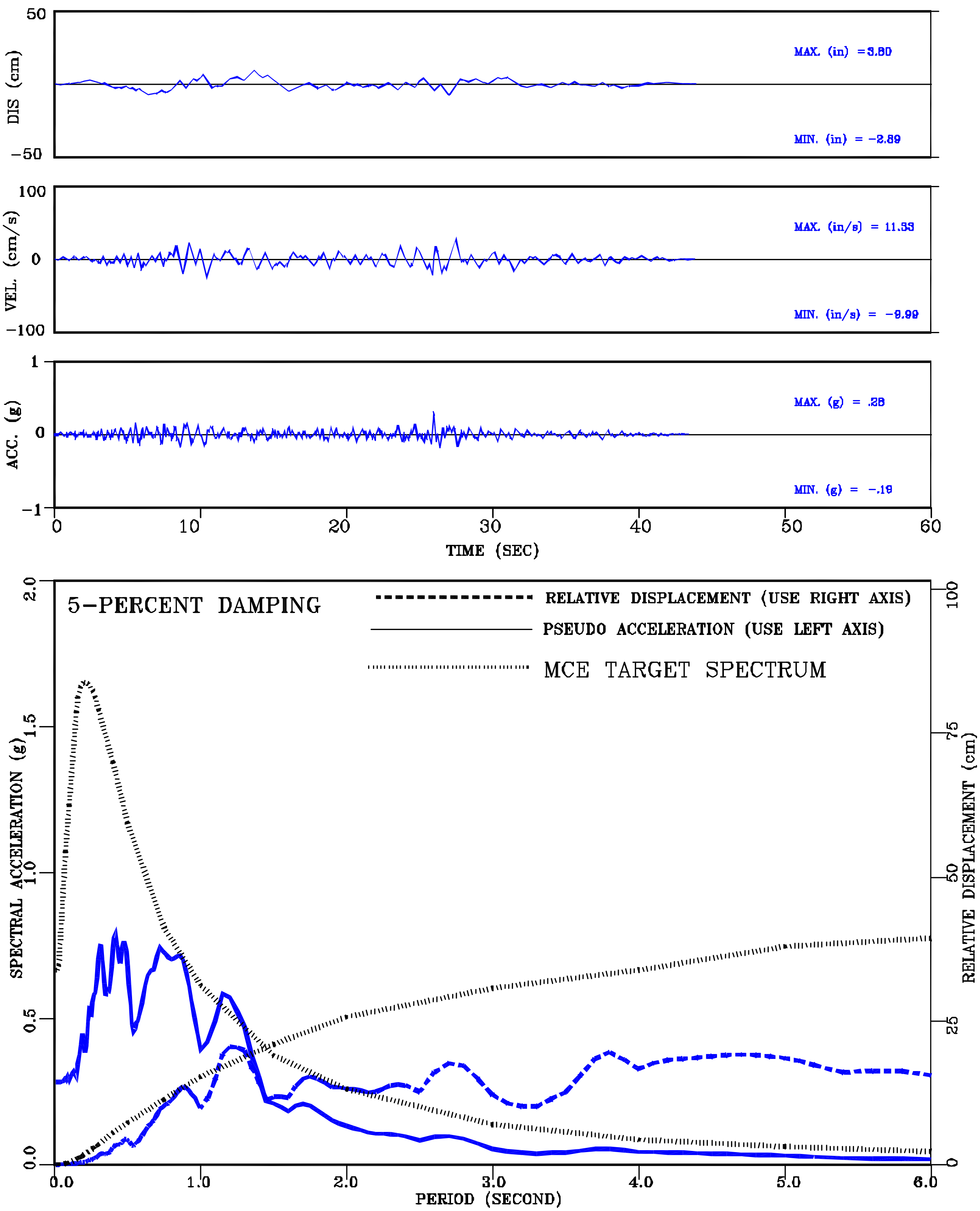
JOSHUA TREE, MAJOR PRINC. COMP MOTION

STARTUP FOR SET 3 FN ROCK MOTION

DEVIL'S SLIDE TUNNELS

EMI Project No.: 01-119	Date:8/20/01

FIGURE B-7



Earth Mechanics, Inc.

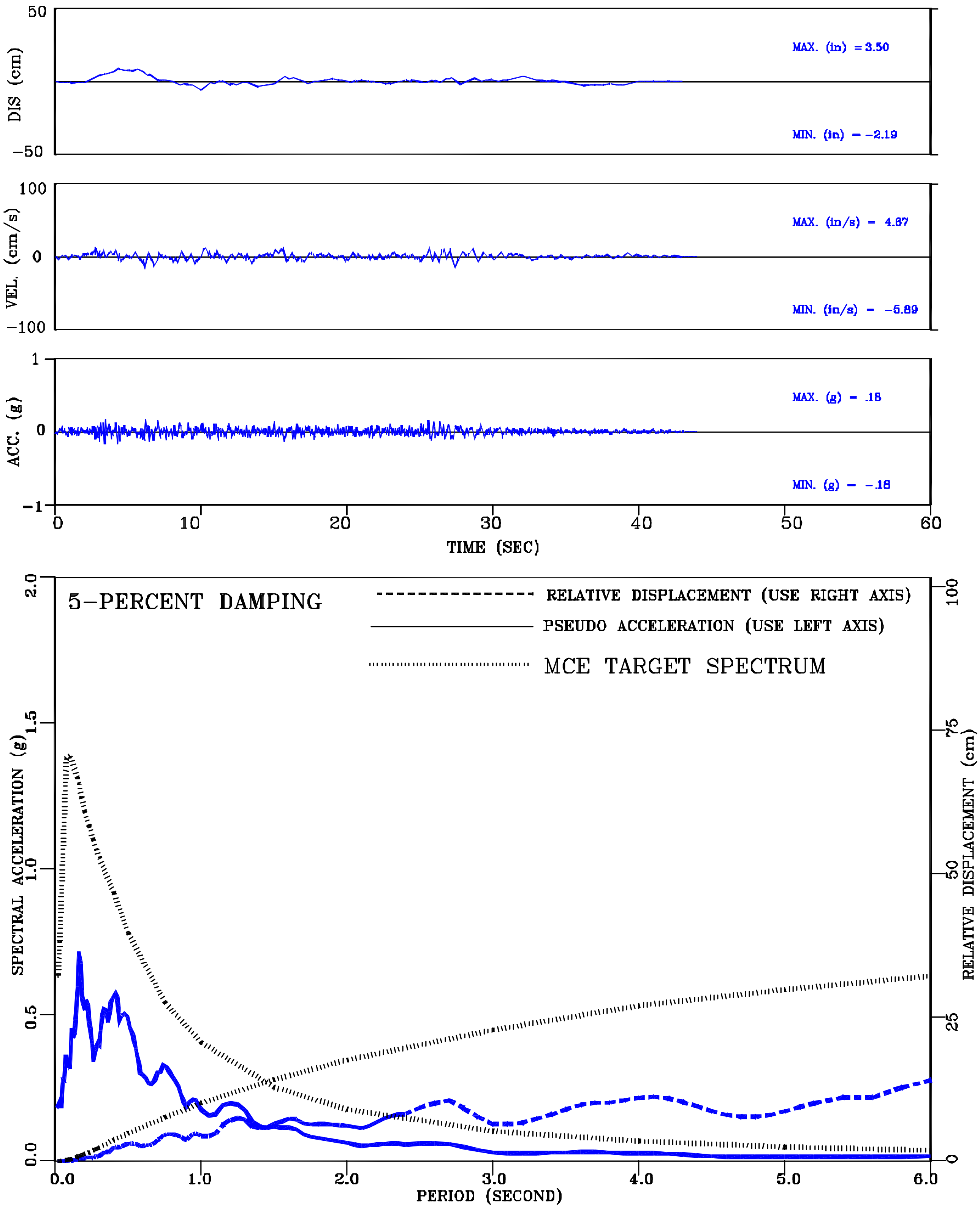
Geotechnical and Earthquake Engineering

DEVIL'S SLIDE TUNNELS

EMI Project No.: 01-119 | Date:8/20/01

JOSHUA TREE, MINOR PRINC. COMP. MOTION
STARTUP FOR SET 3 FP ROCK MOTION

FIGURE B-8



Earth Mechanics, Inc.

Geotechnical and Earthquake Engineering

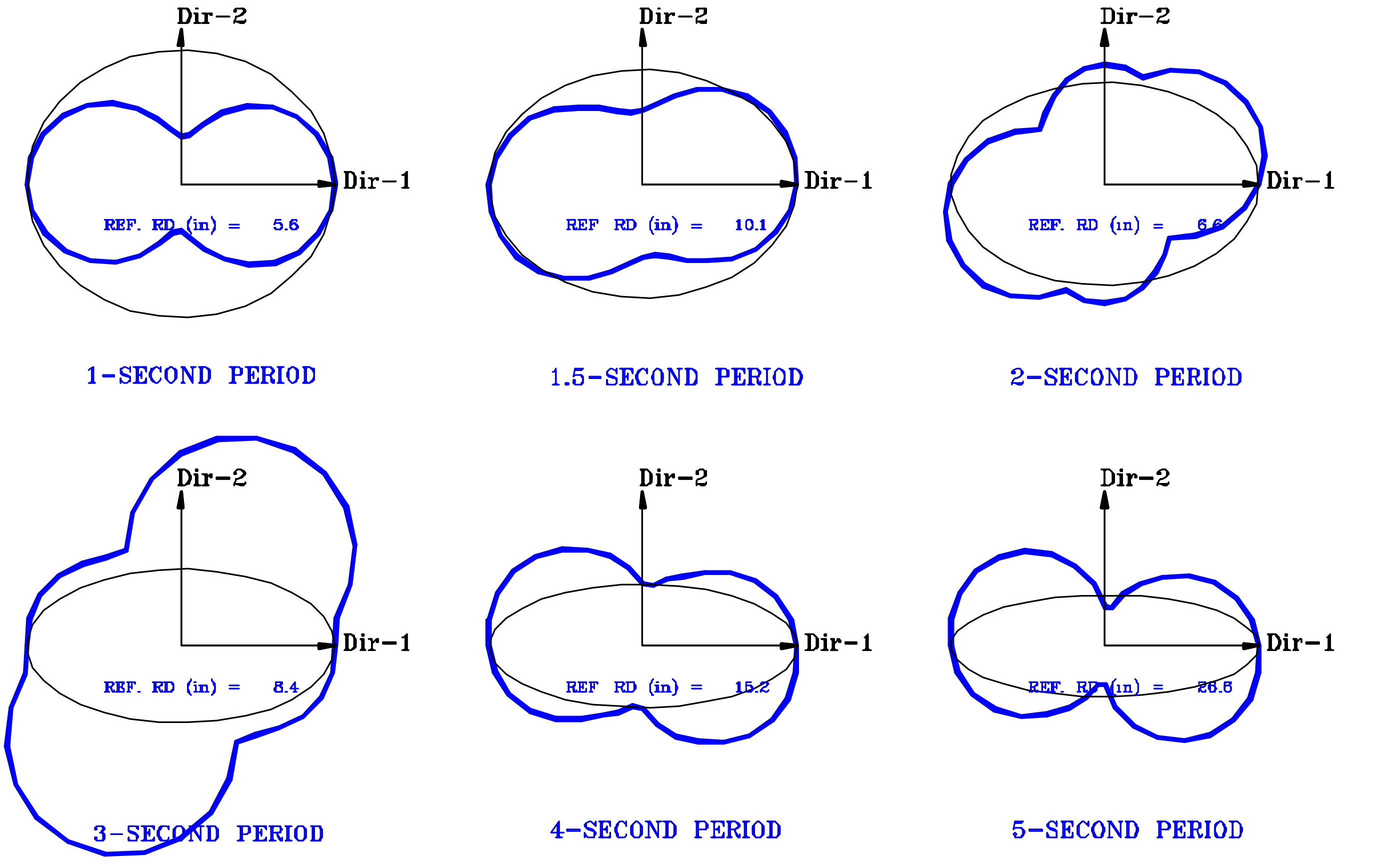
DEVIL'S SLIDE TUNNELS

EMI Project No.: 01-119	Date: 8/20/01

JOSHUA TREE VERT. COMP. MOTION

STARTUP FOR SET 3 VERT. ROCK MOTION

FIGURE B-9

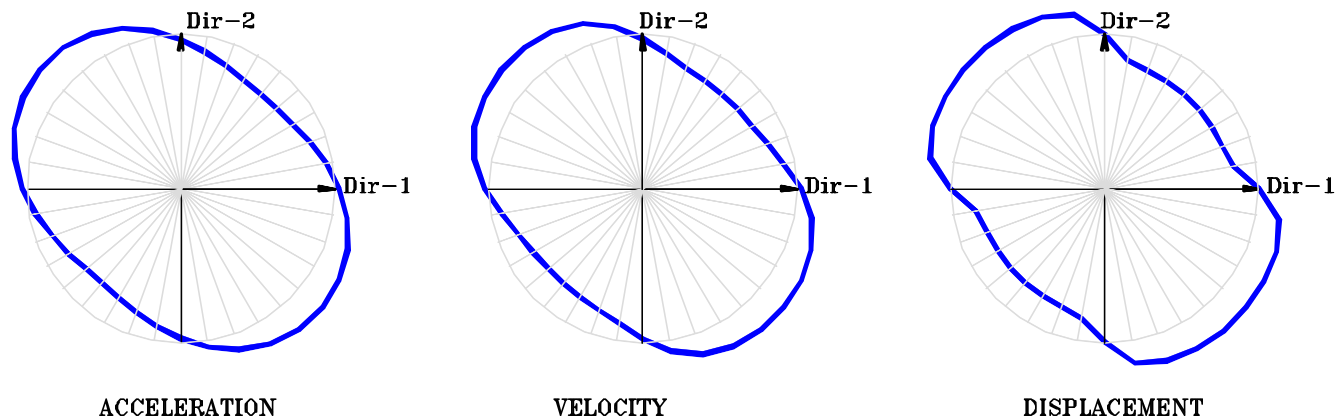


SHAKING INTENSITY AT VARIOUS AZIMUTHS

at Dir-1 = MAJOR PRINCIAL COMPONENT
at Dir-2 = MINOR PRINCIPAL COMPONENT

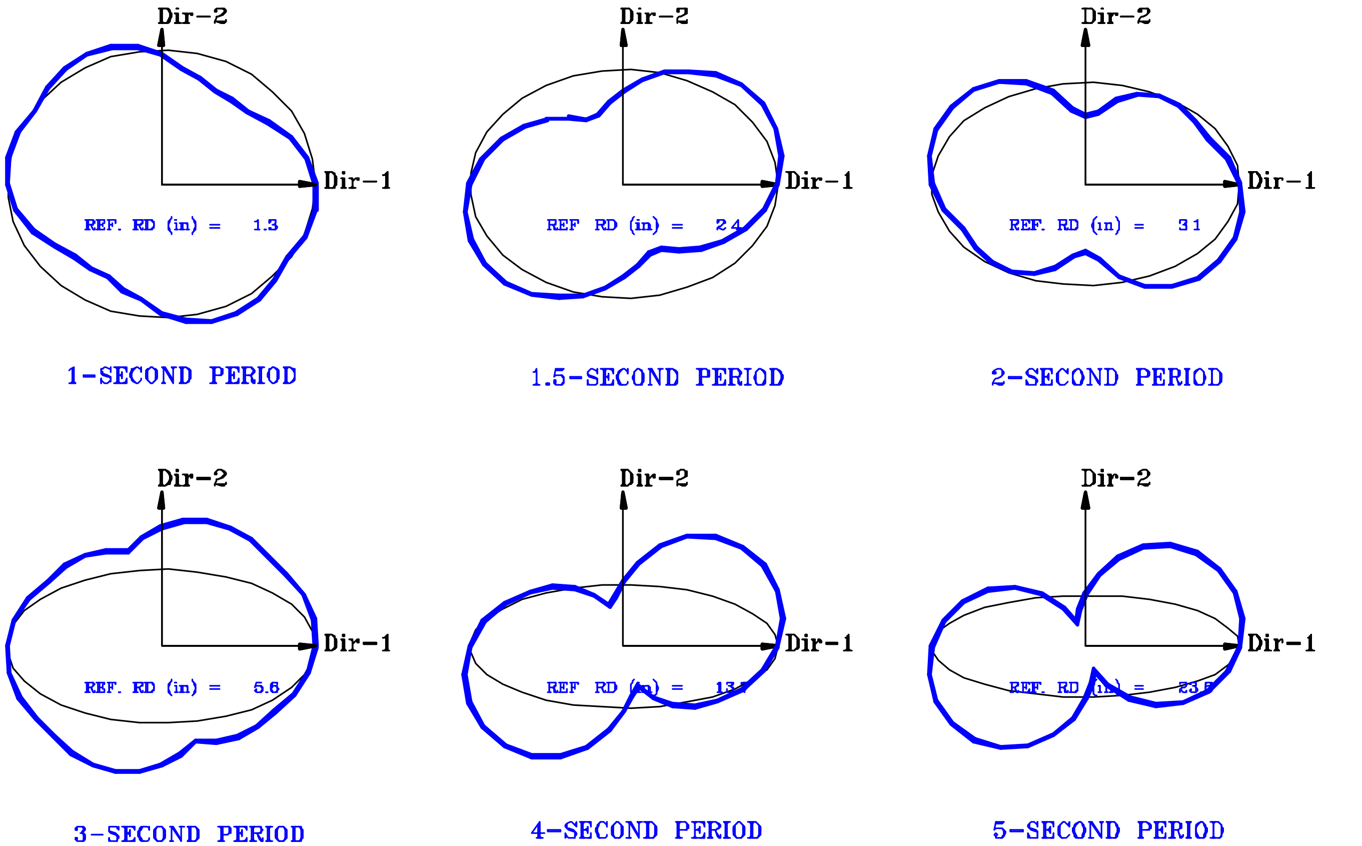
CROSS-CORRELATION STATISTICS FOR Dir-1 and Dir-2

ACCELERATION	VELOCITY	DISPLACEMENT
CROSS CORREL COEFF. = .04	CROSS CORREL. COEFF = .10	CROSS CORREL. COEFF. = 01
PRINC. DIR. AT (DEG) = 4.0	PRINC. DIR. AT (DEG) = 2.8	PRINC. DIR. AT (DEG) = .1
MAX. COEFFICIENT = .250	MAX. COEFFICIENT = .710	MAX. COEFFICIENT = .943
AT DIRECTION (DEG)= 140.0	AT DIRECTION (DEG)= 140 0	AT DIRECTION (DEG)= 140 0



CROSS CORRELATION COEFFICIENT OF RECORDS UNDER ROTATION

Earth Mechanics, Inc.	DEVIL'S SLIDE TUNNELS	CROSS-CORRELATION, YERMO RECORD, STARTUP, FOR SET-1 ROCK MOTION
	PROJECT NO. 01-119	8/20/01	Figure B-10

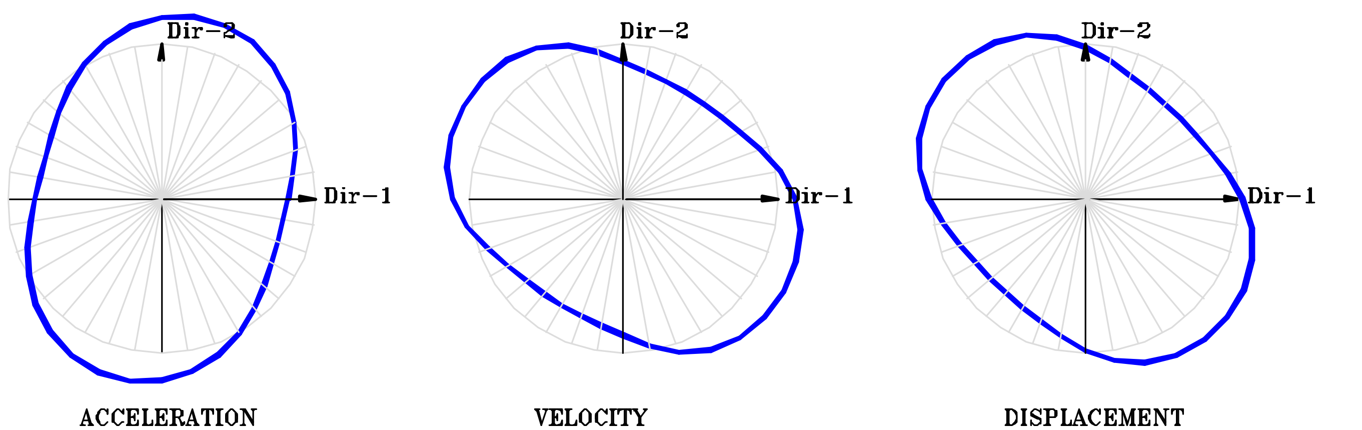


SHAKING INTENSITY AT VARIOUS AZIMUTHS

at Dir-1 =MAJOR PRINCIPAL COMPONENT
at Dir-2 =MINOR PRINCIPAL COMPONENT

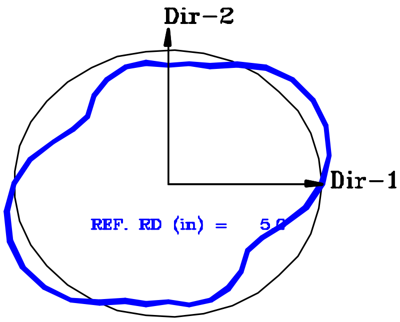
CROSS-CORRELATION STATISTICS FOR Dir-1 and Dir-2

ACCELERATION	VELOCITY	DISPLACEMENT
CROSS CORREL COEFF. = -.19	CROSS CORREL COEFF = .38	CROSS CORREL. COEFF. = .05
PRINC. DIR. AT (DEG) = -30.7	PRINC. DIR. AT (DEG) = 13.6	PRINC. DIR. AT (DEG) = 2.2
MAX. COEFFICIENT = .217	MAX. COEFFICIENT = .666	MAX. COEFFICIENT = .527
AT DIRECTION (DEG)= 80.0	AT DIRECTION (DEG)= 330.0	AT DIRECTION (DEG)= 140.0

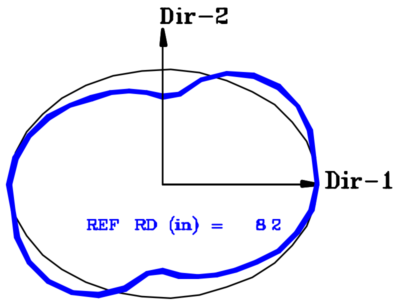


CROSS CORRELATION COEFFICIENT OF RECORDS UNDER ROTATION

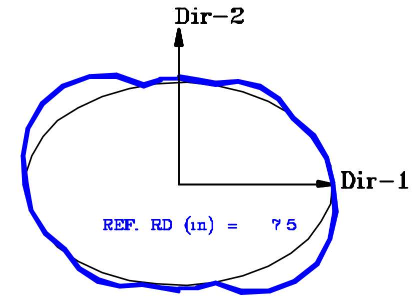
Earth Mechanics, Inc.	DEVIL'S SLIDE TUNNELS	CROSS-CORRELATION, TURKEY ARCELIK RECORD STARTUP FOR SET 2 ROCK MOTION
	PROJECT NO. 01-119 / 8/20/01	Figure B-11



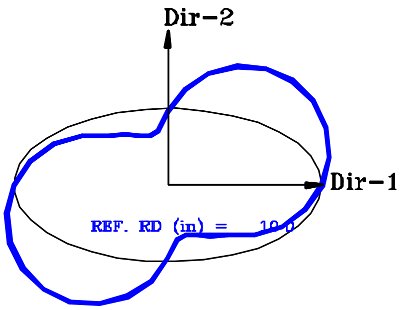
1-SECOND PERIOD



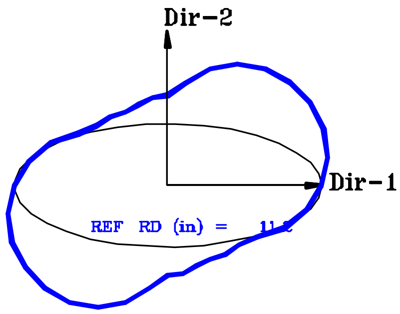
1.5-SECOND PERIOD



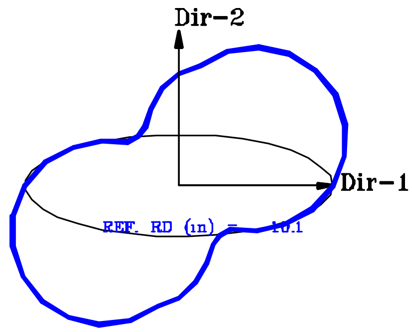
2-SECOND PERIOD



3-SECOND PERIOD



4-SECOND PERIOD



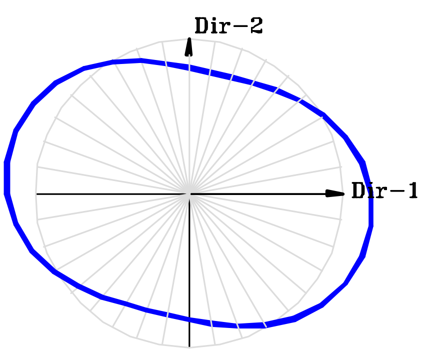
5-SECOND PERIOD

SHAKING INTENSITY AT VARIOUS AZIMUTHS

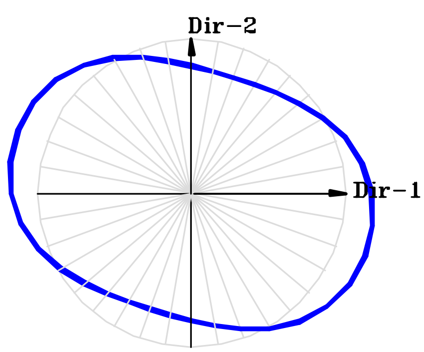
at Dir-1 = MAJOR PRINCIAL COMPONENT
at Dir-2 = MINOR PRINCIPAL COMPONENT

CROSS-CORRELATION STATISTICS FOR Dir-1 and Dir-2

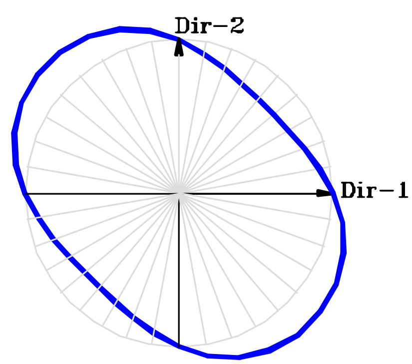
ACCELERATION	VELOCITY	DISPLACEMENT
CROSS CORREL. COEFF. = .26	CROSS CORREL. COEFF = .38	CROSS CORREL. COEFF. = .01
PRINC. DIR. AT (DEG) = 31.5	PRINC. DIR. AT (DEG) = 27.9	PRINC. DIR. AT (DEG) = .5
MAX. COEFFICIENT = .291	MAX. COEFFICIENT = .442	MAX. COEFFICIENT = .414
AT DIRECTION (DEG)= 170.0	AT DIRECTION (DEG)= 340 0	AT DIRECTION (DEG)= 140 0



ACCELERATION



VELOCITY



DISPLACEMENT

CROSS CORRELATION COEFFICIENT OF RECORDS UNDER ROTATION

Earth Mechanics, Inc.	DEVIL'S SLIDE TUNNELS	CROSS-CORRELATION, JOSHUA TREE RECORD STARTUP FOR SET-3 ROCK MOTION
	PROJECT NO. 01-119	8/20/01	Figure B-12